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A COMPUTER ANALYSIS OF A TRI-MOORED BUOY STRUCTURE WITH AN INTE--ETC(U)

MAY 72 S C PAHUJA, R W CORELL

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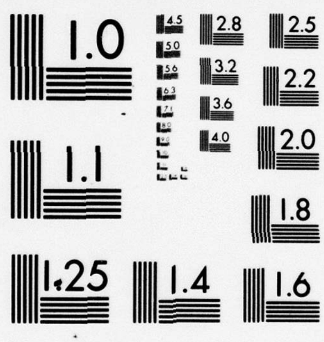

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A Computer Analysis Of a Tri-Moored Buoy Structure With an Internally Redundant Horizontal Structural Element

S. C. Pahuja

R. W. Corell

Report to the Office of Naval Research

Technical Report 110 **May 1972**

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9 Technical Report No. 14 TR-110

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By

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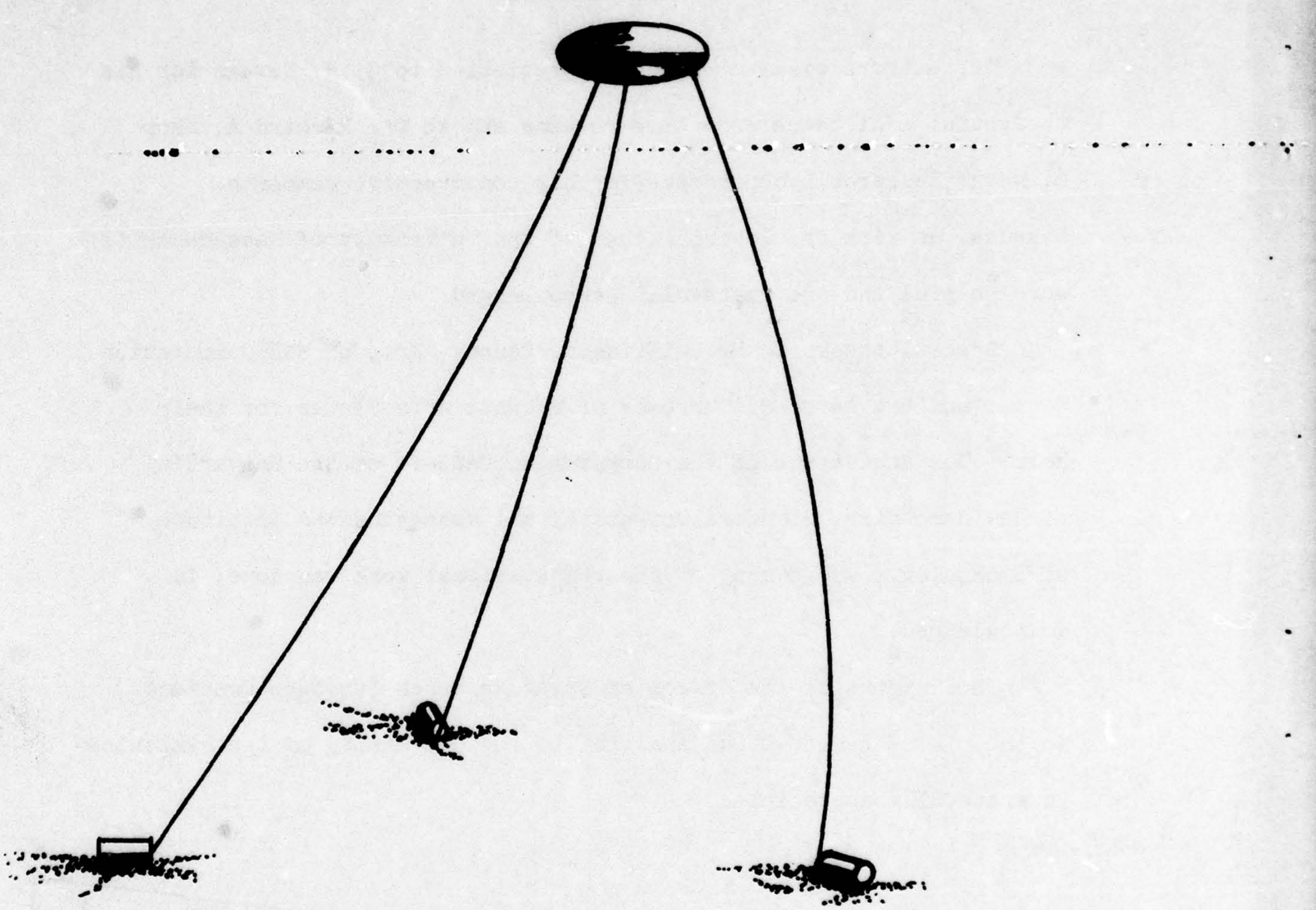

Figure 1: Tri-Moored Subsurface Float with Neutrally Buoyant Legs

ABSTRACT

This report is concerned with the analysis and computer simulation of a tri-moored oceanic buoy structure having a near-horizontal cable connected between two of the three main (see Figure 1) legs. The Method of Imaginary Reactions is used in conjunction with the Method of Successive Approximations to determine the equilibrium configuration of the cable array. A special technique is developed to extend the above methods to include cable arrays with one internally redundant loop. Computer search routines are developed to ensure convergence to the solution for equilibrium positions of the cable array.

The analysis permits the inclusion of discrete elements and floating devices distributed along all cables. Expressions are derived in detail for the hydrodynamic forces. Both tangential and normal drags are included in the calculation of these forces; however, the forces induced by wave action are not considered.

A computer program for implementing the analysis is included, and a sample output appears in Appendix I.

The work reported herein was conducted during the period of September 1968 through December 1970.

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SYMBOLS AND NOTATIONS

The symbols and notations used in this report are defined as they appear in the context. The most important ones are listed here for reference:

A. Symbols as used for Tri-Moored Structure

(a_n, b_n, c_n)	the coordinates of the nth cable anchor
$A_{k, m,n}$	the effective cross-sectional area of the (k,m,n)th elemental device
XTEN(m,n)	the extensional rigidity of the (m,n,)th cable segment
$C^{c;x}_{m,n}$, $C^{c;y}_{m,n}$, $C^{c;z}_{m,n}$	the drag constants of the (m,n)th cable segment
$C^{e;x}_{k,m,n}$, $C^{e;y}_{k,m,n}$	the drag constants of the (k,m,n)th elemental device
$C^{D}_{k,m,n}$	the coefficient of drag of the (k,m,n)th elemental device
$C^{N}_{m,n}$	the coefficient of drag of the (m,n)th cable segment when this segment is normal to the stream
$C^{P}_{m,n}$	the coefficient of drag of the (M,N)th cable segment when this segment is parallel to the stream
$d_{m,n}$	the diameter of the (m,n)th cable segment
$f^{\eta}_{m,n}$	the component of drag force per unit length in the (m,n) direction
$(F^{x}_{m,n}, F^{y}_{m,n}, F^{z}_{m,n})$	the components of the external force acting at the (m,n)th cable station

$(F^{x}_{M(n),n}, F^{Y}_{M(n),n}, F^{z}_{M(n),n})$ — the components of the imaginary reactions applied to the M(n)th stations of cables 2 and 3

$(h^{c;x}_{m,n},\ h^{c;y}_{m,n},\ h^{c;z}_{m,n})$ — the components of the hydrodynamic force per unit length acting on the (m,n)th cable segment

$(h^{e;x}_{k,m,n},\ h^{e;y}_{k,m,n},\ h^{e;z}_{k,m,n})$ — the components of the hydrodynamic force acting on the (k,m,n)th elemental device

$(H^{c;x}_{m,n},\ H^{c;y}_{m,n},\ H^{c;z}_{m,n})$ — the components of the lumped drag force at the (m,n)th cable station due to the distributed hydrodynamic forces along the cables

$(H^{e;x}_{m,n},\ H^{e;y}_{m,n})$ — the components of the lumped drag force at the (m,n)th cable station due to the hydrodynamic forces on the elemental devices

$(\vec{i}, \vec{j}, \vec{k})$ — unit vectors in the (x,y,z) directions, respectively

(k, m, n) — the index of the Kth elemental device on the mth segment of the nth cable

$\bar{k}(m,n)$ — the total number of elemental devices attached to the (m,n)th cable half-segment adjoining the (m-1,n)th cable station

K(m,n) — the total number of elemental devices attached to the (m,n)th cable segment

$BL_{m,n}$ — the stressed length of the (m,n)th cable segment

$BLO_{m,n}$ — the unstressed length of the (m,n)th cable segment

(m,n) — the index of the mth station or segment on the nth cable

M(n) — the total number of stations or segments on the nth cable

$r^D_{m,n}$	the ratio of drag coefficients for the (m,n)th cable segment = $C^P_{m,n}/C^N_{m,n}$
$(R^x_{m,n}, R^y_{m,n}, R^z_{m,n})$	the components of the resultant force in the (m,n)th cable segment
$s_{k,m,n}$	the stressed distance of the (k,m,n)th elemental device from the (m-1,n)th cable station
$\bar{s}_{k,m,n}$	the unstressed distance of the (k,m,n)th elemental device from the (m-1,n)th station
$T_{m,n}$	the tension in the (m,n)th cable segment
$V(m,n : \Xi_1, \Xi_2)$	the integral of $V^2(z)$ along the (m,n)th cable segment from Ξ_1 to Ξ_2 equal to $\int_{\Xi 1}^{\Xi 2} V^2 \, [Z(m,n:\xi)] d\xi$
$w^c_{m,n}$	the weight (or buoyancy) per unit length in water of the (m,n)th cable segment
$w^e_{k,m,n}$	the weight (or buoyancy) in water of the (k,m,n)th elemental device
$W_{m,n}$	the lumped weight (or buoyancy) force at the (m,n)th cable station
(x,y,z)	fixed Cartesian coordinates
$(x_{m,n}, y_{m,n}, z_{m,n})$	the coordinates of the (m,n)th cable station
$z(m,n:\xi)$	the parametric representation of z along the (m,n)th cable segment = $Z_{m-1,n} + \gamma_{m,n}\xi$
$(\alpha_{m,n}, \beta_{m,n}, \gamma_{m,n})$	the direction cosines of the (m,n)th cable segment
$\nabla_{m,n}$	the sine of the angle between the (m,n)th cable segment and the stream

$(\Delta F^{x}_{M(n),n}, \Delta F^{y}_{M(n),n}, \Delta F^{z}_{M(n),n})$	the components of the additive forces applied to the M(n)th stations of cables 2 and 3
$\mu^{c}_{m,n}$	the hydrodynamic constant of the (m,n)th cable segment = $N_{PCm,n}d_{m,n}/2$
$\mu^{e}_{k,m,n}$	the hydrodynamic constant of the (k,m,n)th elemental device = $PC^{D}_{k,m,n}A_{k,m,n}/2$

B. <u>Symbols As Used for Tie Leg</u>

$A_{k,m}$	the effective cross-sectional area of the (k,m)th elemental device
XXTEN(m)	the extensional rigidity of the m th cable segment
$C^{c:x}_{m}$, $C^{c:y}_{m}$, $C^{c:z}_{m}$	the drag constants of the m th cable
$C^{e:x}_{m}$, $C^{e:y}_{m}$, $C^{e:z}_{m}$	the drag constants of the (k,m)th elemental device
$C_{j,m}$	the coefficient of drag of the (k,m)th elemental device
C^{N}_{m}	the coefficient of drag of the m th cable segment when this segment is normal to the stream
C^{D}_{m}	the coefficient of drag of the m th cable segment when this segment is parallel to the stream
d_{m}	the diameter of the m th cable segment
f	the component of drag force per unit length in the m direction
$(F^{x}_{m}, F^{y}_{m}, F^{z}_{m})$	the components of the external force acting at the m th cable station
$(h^{c:x}_{m}, h^{c:y}_{m}, h^{c:z}_{m})$	the components of the hydrodynamic force per unit length acting on the mth cable segment

$(h_m^{e:x}, h_m^{e:y}, h_m^{e:z})$	the components of the hydrodynamic force acting on the (k,m)th elemental device
$(H_m^{c:x}, H_m^{c:y}, H_m^{c:z})$	the components of the lumped drag force at the m th cable station due to the distributed hydrodynamic forces along the cables
$(H_m^{e:x}, H_m^{e:y}, H_m^{e:z})$	the components of the lumped drag force at the mth cable station due to the hydrodynamic forces on the elemental devices
$\vec{i}, \vec{j}, \vec{k}$	unit vectors in the (x,y,z) directions, respectively
(j,m)	the index of the jth elemental device on the mth segment
$\bar{j}(m)$	the total number of elemental devices attached to the mth cable half-segment adjoining the (m-1)th cable station
j(m)	the total number of elemental devices attached to the mth cable segment
B(m)	the stressed length of the mth cable segment
L(M)	the unstressed length of the m th cable segment
(m)	the index of the mth station
r_m^D	the ratio of drag coefficients for the mth cable segment = c_m^F / c_m^D
R_m^w, R_m^y, R_m^z	the components of the resultant force in the mth cable segment
$S_{k,m}$	the stressed distance of the (k,m)th elemental device from the (m-1) cable station
$\bar{S}_{k,m}$	the unstressed distance of the (k,m)th elemental device from the (m-1)th station

ST_m	the tension in the mth cable segment
$V(m:\Xi_1, \Xi_2)$	the integral of $V^2(z)$ along the mth cable segment from Ξ_1 to Ξ_2 $\int_{\Xi 1}^{\Xi 2} V^2[Z(m : \xi (]\ d\xi$
W_m^c	the weight (or buoyancy) per unit length in water of the mth cable segment
$W_{k,m}^e$	the weight (or buoyancy) in water of the (k,m)th elemental device
W_m	the lumped weight (or buoyancy) force at the mth cable station
(x,y,z)	fixed Cartesian coordinates
(X_m, Y_m, Z_m)	the coordinates of the m th cable station
$Z(m,\xi)$	the parametric representation of z along the mth cable segment = $Z_{m-1} + \gamma_m \xi$
$(\alpha_m, \beta_m, \gamma_m)$	the direction cosines of the mth cable segment
Δ_m	the sine of the angle between the mth cable segment and the stream
μ_m^c	the hydrodynamic constant of the mth cable segment = $PC_m^N\ d_{m/2}$
$\mu_{k,m}^e$	the hydrodynamic constant of the (k,m)th elemental device = $P C^D_{k,m}\ A_{k,m/2}$
ξ	a parameter defining distance along the mth cable segment

$(\Gamma_m, \pi_m, \eta_m)$	respectively, unit vectors along the mth cable segment, normal to both the mth cable segment and the stream, and normal to the mth cable segment but in the plane that includes this segment and the stream

C. Symbols that are Common to Both the Main and the Tie Leg Arrays

COMPD	a cut off value that defines the acceptable completion of the successive approximation iteration
COMPE	a cut off value that defines the acceptable completion of the Imaginary Reaction iteration
E	a positive definite error function
$\vec{V}$	the current vector
V(z)	the current magnitude at a height z above the bottom
δ	a positive convergence factor having the dimensions of force
ρ	the density of surrounding fluid
Ø	the angular dir^n of the current with respect to x axis

INTRODUCTION

The problem of determining undersea cable configurations due to applied loadings at known positions along the cable has received considerable attention in the past (2,5,8,9)*. However, the solutions have pertained generally to particular loading conditions. A general closed-form analytical method solving a large variety of complex cable systems has not been available, primarily because of the nonlinear characteristic of the differential equations describing these systems.

Alekseev[1] dealt with the problem of a free-ended cable from a continuum point of view. He obtained a three-dimensional solution to the equilibrium equations, which included gravity effects, along with arbitrarily applied forces along the cable. Pode[6] also used the continuum approach to deal with the above problem. However, in treating a towed body, he only considered a special case of the general problem. Both Alekseev and Pode assumed an inextensible cable so that the exact integration of the equilibrium equations could be obtained. Therefore, these solutions are independent of the materials used for the towing cables.

Walton and Polachek[10] approached the problem of a free-ended cable from a lumped parameter point of view. They developed a two-dimensional numerical solution for an inelastic line in water when the end conditions are assumed. Paquette and Henderson[5] followed a procedure similar to that of Walton and Polachek using analog computer techniques. The cable was

*Numbers within parentheses refer to references given on page 73.

considered to be elastic but constraints were placed on the equilibrium position of the cable stations. Both steel and nylon cables were considered. O'Brien[2] considered the case of fixed end elastic cables, such as transmission lines. An exact continuum solution to the problem was obtained; however, the forces applied to the cable were assumed to be constant over sections of prescribed length so that the shape of the cable segments could be expressed as an elastic catenary.

Skop and O'Hara[8] developed a technique called the Method of Imaginary Reactions, which is an extension of classical consistent deformation theory to a nonlinear problem. As reported in Reference 8 & 9 the method applies to elastic non-redundant cable systems and uses lumped parameter representations of the external forces. The technique employs a numerical analysis method that uses a set of straight segments to represent the cable. This enables the non-linear system to be represented by a set of linear equations. By prescribing a simple method of varying the redundant reactions, an iteration technique is used which converges to the correct reactions (and consequently the correct static equilibrium configuration). The method is globally convergent and converges to actual reactions from any set of initially estimated reactions. The only restriction reported by the authors (Reference 8 & 9) is that the method is not applicable if internal loops (a redundant structure) exist in the cable system.

Savage and Sniffin[7] have analyzed a tri-moored subsurface float with neutrally buoyant mooring legs (see Fig. 1), utilizing a three-dimensional solution that assumes that the neutrally buoyant legs have a catenary shape under the effect of current. They also assume that if the

variation of current velocity with depth is moderate, the use of root mean square velocity as a uniform velocity profile results in good approximation of the cable shapes.

Skop and Kaplan[9] applied their method to determining the static configuration of a buoy cable array like the one analyzed by Savage and Sniffin. The cable array is loaded by weights and buoyancy forces and by current-induced hydrodynamic forces which are functions of both the orientation and depth of the cables in water. The Method of Successive Approximations is combined with the Method of Imaginary Reactions to analyze the position dependent forces. Provision is made to allow for varying current profile and a three-dimensional solution is developed.

This analysis uses the Method of Imaginary Reactions to simulate and analyze a structure which is similar to the one dealt with by Skop and Kaplan except for the addition of a near-horizontal cable attached to any two points on the array of the structure. This structure is diagrammatically shown in Figure 2.

Skop and O'Hara[8] reported the inapplicability of the Method of Imaginary Reactions to structures that have internal loops, although they have recently published a report which removes this restriction.[12] The structure analyzed in this report has one internal loop. Therefore, the purpose of this engineering research is to develop a technique which overcomes the Skop/O'Hara restriction and show that the Method of Imaginary Reactions can be used to analyze a structure with at least one internal loop

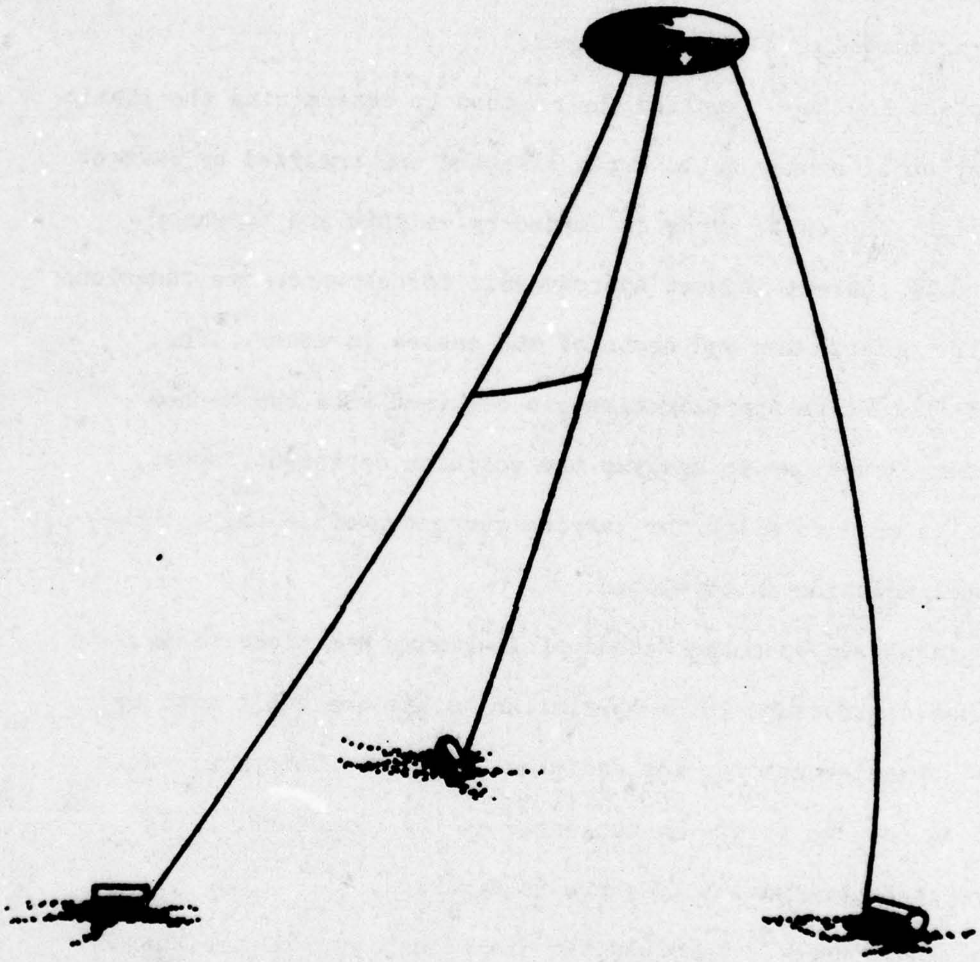

Figure 2: The Tri-Moored Array Structure with a Horizontal

Element Between Two Cables

Since the work of Pahuja[11], Skop and O'Hara have generalized the Method of Imaginary Reactions to handle the redundant structural cable array.[12] This report, summarizing the research work of Pahuja published in 1970, describes the use of the Method of Imaginary Reactions in the analysis of a single loop cable array. The appendix contains the computer program developed which has been compiled on an IBM 360/40 facility.

CHAPTER I

METHOD OF IMAGINARY REACTIONS

A. Background

A classical method for the analysis of indeterminate structures is the method of consistent deformation, the method of consistent distortion or displacement as developed by James Clark Maxwell.[4] This method of indeterminate reaction analysis utilizes equations of compatibility of the structure to supplement the equations of equilibrium to obtain a solution to the unknown redundants. The following assumptions are made in this type of method:

1. The structure is assumed to be linear, i.e., the loads applied are proportional to the displacements and the displacements are relatively small.
2. That there are no gross structural distortions or instabilities upon the release of redundant reactions, i.e., upon the release of the "redundant reaction" the basic geometry of the structure should not change.

The above two conditions are generally not met in the analysis of cable arrays.

The Method of Imaginary Reactions [8] overcomes these restrictions for the analysis of cable systems. It is, however, a natural extension of classical consistent deformation theory.

The method uses the following assumptions:

1. The bending stiffness of the cable is neglected.

2. The external forces acting on the cable arrays are "lumped" at stations or nodes along the cable.

3. The cable array is always statically stable, i.e., under the action of applied forces, no cable segment has zero tension.

The first two assumptions are made to help simplify the problem. If the cable length is divided into segments, then each cable segment between stations can be assumed straight. The analysis technique provides the equilibrium configuration of the system (including the effect of cable stretching) which is determined uniquely from formulas that are functions of only the applied forces and the reactions. This offers an advantage, in that the solution is now dependent upon the number of external redundant reactions and not on the number of stations, which are arbitrary. The third assumption is necessary, because even though convergence is still obtained, when this condition is not met the configuration is no longer uniquely described by the method.

B. Description of the Method of Imaginary Reactions

1. Basic Concepts

This method, as adapted to cables by Skop and O'Hara[8] is explained briefly in this section. Consider a single cable array of two-dimensional applied forces (the method is not restricted to two dimensions)as shown in Figure 3.

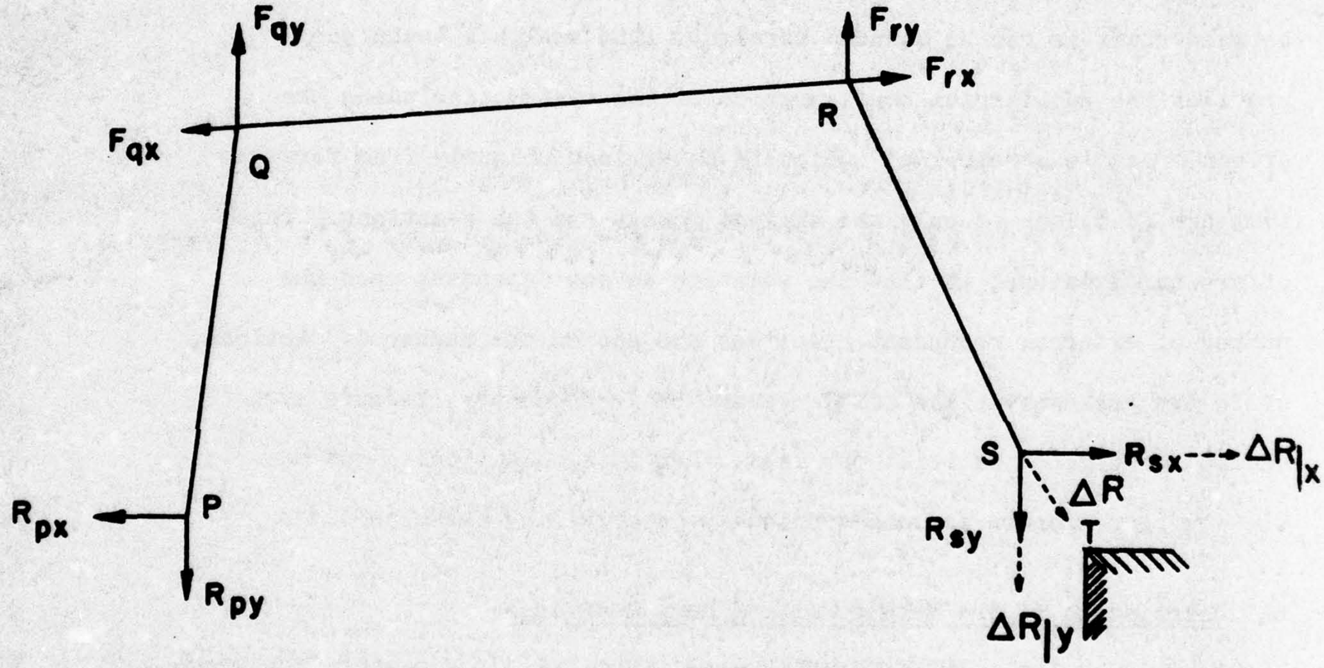

Figure 3: Basic Concepts of the Single Cable

In Figure 3, Rsx and Rsy acting at point S, Frx and Fry acting at point R, Fqx and Fqy acting at point Q, are externally applied and are known. If P be designated as the anchor point, then the reaction components Rpx and Rpy can be determined simply by summation of forces in the x and y directions.

Since these reactions are known, the tension in segment PQ, the length of segment PQ under the tension and the coordinates of point Q become known in that order by the use of elementary statics. Using the same type of analysis the coordinates of point R and S can also be found. Once the position of these points is known, we have obtained the equilibrium configuration of the free-ended cable. If point S happens to be the second anchor point, then the fixed-ended cable system is in equilibrium in the desired configuration. In general, however, we are not at the desired fixed end anchor point, pt. T, but rather at point S. Therefore anchor point reactions Rsx and Rsy at point S are not the actual anchor point reactions which place the cable end at the desired anchor point (T). The Method of Imaginary Reactions provides the methodology for finding the actual reactions at point T which will force point S to move over to the anchor point (T), producing the true equilibrium configuration of the system.

This is done by first applying a small force ΔR at point S vectorially directed in a direction from S towards T. If the coordinates of point T are (Tx, Ty) and those of point S are (Sx, Sy), then the ratio of the component of this additional force [$(\Delta R)x$ & $(\Delta R)y$] is given by:

$$\frac{(\Delta R)x}{(\Delta R)y} = \frac{Tx - Sx}{Ty - Sy} \qquad (4,1)^*$$

*The numbering of all important equations is based upon the format (a,b) where a is the number of an equation in a given chapter b. (Equations (1,1) - (3,1) have been deleted from the text.)

The magnitude of these components is defined by:

$$(\Delta R)_x = \frac{\delta}{\sqrt{E}} (Tx - Sx) \tag{5,1a}$$

$$(\Delta R)_y = \frac{\delta}{\sqrt{E}} (Ty - Sy) \tag{5,1b}$$

where $E = (Tx - Sx)^2 + (Ty - Sy)^2$ is the measure of error between the equilibrium position calculated using an estimated or guessed reaction and the correct equilibrium position. E is always positive and vanishes uniquely only when the correct equilibrium has been obtained. In other words, $E \to 0$ only when $Tx = Sx$ and $Ty = Sy$ simultaneously. However, to arrive at the correct equilibrium configuration, it is necessary to assure that E will become vanishingly small. To assure convergence, a positive number, δ , having the dimensions of the force, is introduced. δ is a convergence parameter used to select the magnitude of the additive force ΔR (as demonstrated in equations (5,1)) in a manner that the cable array will converge to the correct equilibrium configuration. Referring back to equations (5,1), the ratios $(Tx - Sx)/\sqrt{E}$ and $(Ty - Sy)/\sqrt{E}$ are of bounded variation (lying between -1 and +1), and E will become vanishingly small only when $\delta \to 0$. When this happens, the additive forces $(\Delta R)x$ and $(\Delta R)y$ are zero, and we have the correct reactions and thus the correct equilibrium configuration.

The algorithm for obtaining a solution is:

1. Make a reasonable engineering guess as to the components of the reaction at the redundant anchor (References 8,9, & 11 discuss methods for making these guesses).
2. Release the redundant anchor , i.e.,point S, while maintaining the guessed component reaction forces. This results in the creation of a free-ended cable.

3. Calculate the equilibrium position using static force equilibrium and compute the quantities (Tx - Sx), (Ty - Sy) and E.

4. Choose an initial value for δ so that the value of $(\Delta R)_x = \frac{\delta}{\sqrt{E}}$ (Tx-Sx), and $(\Delta R)y = \frac{\delta}{\sqrt{E}}$ (Ty-Sy) can be found. δ can be chosen initially to be very large, since it will of necessity become smaller as the solution proceeds step by step.

5. Step 4 results in an additive force equal to $R' = R + \Delta R$ acting at the assumed free end. Apply this additive force and find the new equilibrium position of the cable.

6. The next step involves comparing the value of E' (the new measure of error) with E (the previous measure of error.). Two possible situations can exist:

   a. If $E'<E$, then a successful step has been made because the aim is to reduce the new value of E to zero. In this case the same value of δ is retained and a new value of the additive force (ΔR) is calculated and added to the previous R to calculate again a new equilibrium position. Repeat the process until a stage where $E' > E$.

   b. If $E<E'$, then δ is too large. The new values that resulted in the new measure of error E' are rejected. Go back to the last iteration which gave the previous measure of error E. Then, reduce δ by halving its value. Then proceed in a repetitive manner with steps 4 through 6, until the value of E is arbitrarily small, at which point the released end is arbitrarily close to the real anchor position, and hence, a solution to the problem has been obtained. Figure 4 is a flow diagram describing the procedure.

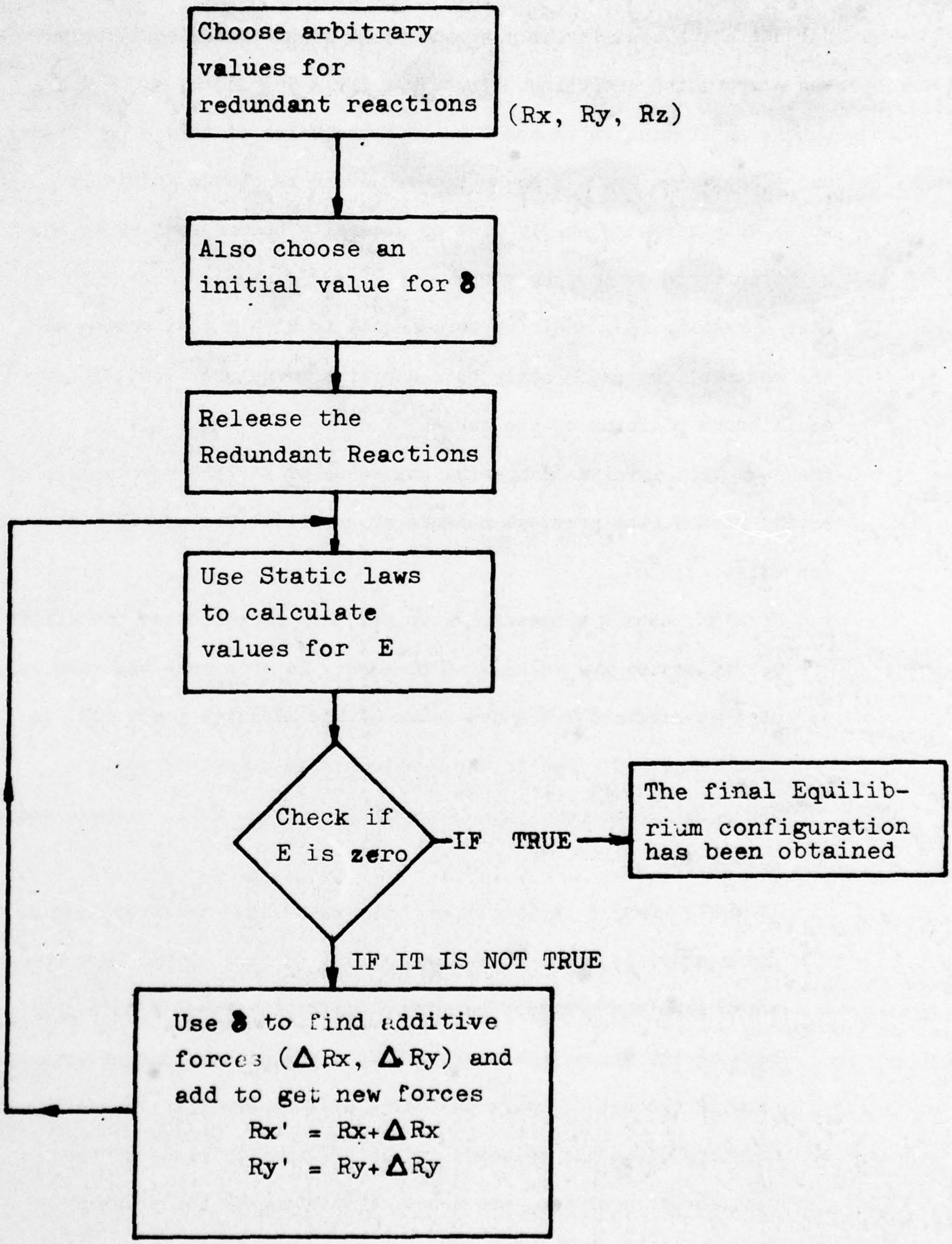

Figure 4: A Flow Diagram Describing the Method of Imaginary Reactions

This application of Imaginary Reactions is globally convergent [(8)]; i.e., no matter what the initial guessed reactions are, the calculation converges to the correct coordinates*.

2. LUMPED PARAMETER REPRESENTATION

One of the assumptions made during the development of the Method of Imaginary Reactions is that the distributed forces that act on the cable array can be represented by lumped forces at specified points on the cable. This assumption is required if the paths to the free ends of the system are to be determined by elementary statics and formulas that express the elongation of the cables under tension. The only condition that these elongation formulas have to meet is that the cable length increases with the increase in tension and be a single valued function; therefore, the elongation formulas can be either linear or non-linear.

Some of the guidelines for a successful lumped parameter representation are presented below:

1. Each cable in the array is represented by at least two stations, one at each end.
2. Each point of discontinuity in a physical property of a cable is represented by a station. Consequently, each cable segment in the array is homogeneous with constant characteristics. The cable can be described by as many stations (segments) as are necessary to represent the cable. Segments into which the cable is divided do not have to be of equal length along the cable array.
3. The method of analysis has no direct bearing on the number of stations on the cable array. As many additional stations as

*The analytical proof can be found in Reference 8.

are necessary to obtain a satisfactory approximation to the continuous equilibrium shape of the array are used. The error function E, the positive δ, and the various values of Δ R do not depend upon the number of stations.

4. The method by which the external forces acting on the array are to be lumped at the cable station is completely arbitrary. In this report a half segment technique suggested by Paquette and Henderson[5] is used.

C. APPLICATION OF THE METHOD OF IMAGINARY REACTIONS TO DETERMINE EQUILIBRIUM CONFIGURATION OF A MULTI-MOORED CABLE SYSTEM

In this section, the Method of Imaginary Reactions is discussed in summary fashion to determine the static equilibrium configuration of a multi-moored cable system. (See Figure 1) A detailed discussion of the analysis of this structure is contained in Reference 9 & 11 . A summary discussion of the application of the Skop & O'Hara method follows as background to the extension to the single internal loop analysis.

1. Definitions

A few definitions, which are helpful in understanding the further text, are listed below.

1. Simple cable array

   A simple cable array is defined as a cable system which contains no closed loops, i.e., it is not internally redundant.

2. A branch point

   A branch point of a simple cable array is defined as a point at which a single cable "splits" into two or more cables.

3. Primary and Secondary Anchors

   Each cable, in any cable system, is denoted by a number (n). The cable is said to terminate at a branch point. The

index n=1 is reserved for the cable that is attached to an anchor point in the system. In case more than one anchor point exists in a system, then the point to which cable number 1 is attached is called the Primary Anchor and the other anchors are called Secondary Anchors. It is the Secondary Anchors that are released and subjected to imaginary reactions.

2. Coordinate System and Notation

For the tri-moored system analysis, a right-handed (x,y,z) cartesian coordinate system is used. The z axis is defined to be parallel to the direction of gravity.

The location of the nth cable anchor is given by a(n), b(n), c(n). Each cable in the system is represented by M(n) stations. The location of the mth station on the nth cable is denoted by

$$(X_{m,n},\ Y_{m,n},\ Z_{m,n},) \tag{21,1}$$

where m = 1,2 M(n).

The stations are counted from the primary anchor to the branch point of the array along cable 1, and from branch point of the array to the secondary anchors along cables 2 and 3 respectively as shown in Figure 5.

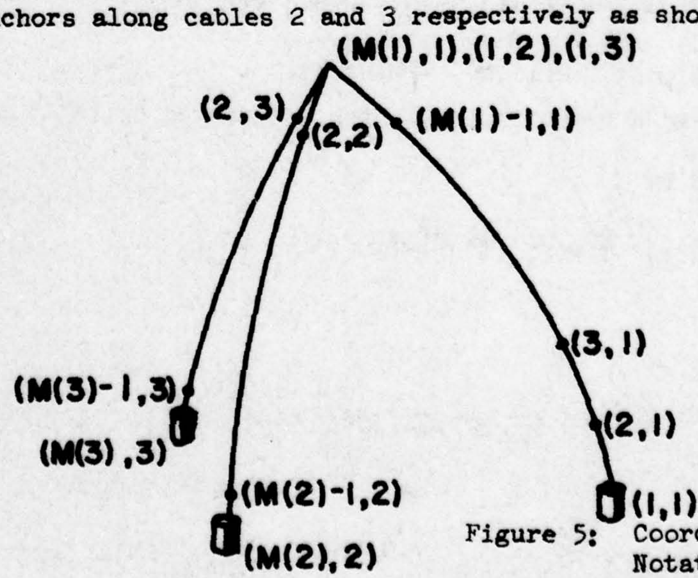

Figure 5: Coordinate Systems and Notations for Tri-Moored Array

Thus, for a branch point

$$X_{(1,2)}=X_{(1,3)}=X_{(M(1),1)} \qquad (22,1a)$$

$$Y_{(1,2)}=Y_{(2,3)}=Y_{(M(1),1)} \qquad (22,1b)$$

$$Z_{(1,2)}=Z_{(2,3)}=Z_{(M(1),1)} \qquad (22,1c)$$

and coordinates of the three anchor points, both primary and secondary are denoted by

$$(X_{(1,1)}, Y_{(1,1)}, Z_{(1,1)}) = (a,b,c) \qquad (23,1a)$$

$$(X_{(M(2),2)}, Y_{(M(2),2)}, Z_{(M(2),2)}) = (a_2, b_2, c_2) \qquad (23,1b)$$

$$(X_{(M(3),3)}, Y_{(M(3),3)}, Z_{(M(3),3)}) = (a_3, b_3, c_3) \qquad (23,1c)$$

The external forces acting at the (m,n) th station are defined by the components along the x,y and z axis:

$$(F^x_{(m,n)}, F^y_{(m,n)}, F^z_{(m,n)}) \qquad (24,1)$$

where m = 1,2 ---M(n)

and n = 1,2,3

Thus, forces acting at an anchor point are represented by

$$(F^x_{(M(n),n)}, F^y_{(M(n),n)}, F^z_{(M(n),n)}) \qquad (25,1)$$

and forces at a branch point, which is indexed by (M(1),1) conventionally, are denoted by

$$F^x_{(M(1),1)}, F^y_{(M(1),1)}, F^z_{(M(1),1)} \qquad (26,1)$$

3. Static Equilibrium Configuration

It was stated earlier that for a two-dimensional cable system if external forces in segments are known, then the tensions in and orientation of the cable segments can be uniquely determined by ordinary static method. This can be generalized to three dimensions and multi-moored cables. The essence of this statement can be summarized as follows:

1. If the external forces applied to the arrays are constant, then the components of the resultant force ($R^X{}_{m,n}$, $R^Y{}_{m,n}$, $R^Z{}_{m,n}$,) acting in the (m,n) th cable segments can be given in terms of the applied external force through the following expressions.

   for m = M(n) and n = 2,3

   $$R^x{}_{M(n),n} = F^x{}_{M(n),n} \qquad (27,1a)$$

   $$R^y{}_{M(n),n} = F^y{}_{M(n),n} \qquad (27,1b)$$

   and

   $$R^Z{}_{M(n),n} = F^Z{}_{M(n),n} \qquad (27,1c)$$

   for m = M(1) and n = 1, the branch point.

   $$R^x_{M(1),1} = F^x_{M(1),1} + R^x_{2,2} + R^x_{2,3} \qquad (28,1a)$$

   $$R^Y_{M(1),1} = F^Y_{M(1),1} + R^Y_{2,2} + R^Y_{2,3} \qquad (28,1b)$$

   $$R^Z_{M(1),1} = F^Z_{M(1),1} + R^Z_{2,2} + R^Z_{2,3} \qquad (28,1c)$$

and for m = 2,3 ---M(n)-1 and n = 1,2,3

$$R^{x}_{m,n} = F^{x}_{m,n} + R^{x}_{m+1,n} \tag{29,1a}$$

$$R^{y}_{m,n} = F^{x}_{m,n} + R^{y}_{m+1,n} \tag{29,1b}$$

$$R^{z}_{m,n} = F^{z}_{m,n} + R^{z}_{m+1,n} \tag{29,1c}$$

Thus starting from the secondary anchor points the forces are very readily summed up to give the reactions at every station.

2. Once the resultant force has been found, the tension $T_{m,n}$ is given by:

$$T_{m,n} = \sqrt{(R^{x}_{m,n})^2 + (R^{y}_{m,n})^2 + (R^{z}_{m,n})^2} \tag{30,1}$$

The tension in each segment results in the elongation of segments and the stressed length is obtained by

$$BL_{m,n} = BL_{o\ m,n}\left[1 + \frac{T_{m,n}}{XTEN(m,n)}\right] \tag{31,1}$$

where $BL_{o\ m,n}$ is unstressed length.

3. The next step is to find coordinates of each station. To start the solution, one starts from the primary anchor because its coordinates are known and are fixed. The coordinates, then, are found from the following equations:

$$X_{m,n} = \frac{BL_{m,n}}{T_{m,n}} R^x_{m,n} + X_{m-1,n} \qquad (32,1a)$$

$$Y_{m,n} = \frac{BL_{m,n}}{T_{m,n}} R^y_{m,n} + Y_{m-1,n} \qquad (32,1b)$$

$$Z_{m,n} = \frac{BL_{m,n}}{T_{m,n}} F^z_{m,n} + Z_{m-1,n} \qquad (32,1c)$$

where $m = 2,3 \quad ...M(n)$

4. In general, for a guessed set of imaginary reactions, the $M(n)$ ends of cable 2 and 3 will not be at the true anchor points. As a measure of the distance of these ends from the correct anchor points, the positive error function E is defined as

$$E = \sum_{n=2}^{3}\{[a_n - X_{M(n),n}]^2 + [b_\eta - Y_{M(n),n}]^2 + [c_\eta - Z_{M(n),n}]^2\} \qquad (33,1)$$

E will uniquely vanish when the true anchor point has been reached.

5. Let the imaginary reactions applied to the ends of cables 2 and 3 be recalculated as

$$(F^x_{M(n),n})' = F^x_{M(n),n} + \Delta F^x_{M(n),n} \qquad (34,1a)$$

$$(F^y_{M(n),n})' = F^y_{M(n),n} + \Delta F^y_{M(n),n} \qquad (34,1b)$$

$$(F^z_{M(n),n})' = F^z_{M(n),n} + \Delta F^z_{M(n),n} \qquad (34,1c)$$

where primes denote the new imaginary reactions and the additive forces are defined by

$$\Delta F^{x}_{M(n),n} = \frac{\delta}{\sqrt{E}} [a_n - x_{M(n),n}] \quad (35,1a)$$

$$\Delta F^{y}_{M(n),n} = \frac{\delta}{\sqrt{E}} [b_n - y_{M(n),n}] \quad (35,1b)$$

$$\Delta F^{z}_{M(n),n} = \frac{\delta}{\sqrt{E}} [c_n - z_{M(n),n}] \quad (35,1c)$$

The quantity δ as defined earlier, is the positive convergence factor. Thus the correct equilibrium configuration is obtained once $E \to 0$.

Thus, in the above section the use of the Method of Imaginary Reactions to find equilibrium configuration of a tri-moored structure has been demonstrated. From here the method can be extended for n number of cables easily.[8]

D. APPLICATION OF METHOD OF IMAGINARY REACTIONS FOR POSITION-DEPENDENT EXTERNAL FORCES

In the preceding section the ability of the Method of Imaginary Reactions to determine the equilibrium configuration of a cable array, both single and multi-moored has been demonstrated. However, the use of this method to determine equilibrium configuration by simple statics was dependent totally upon the lumped external forces being constant.

However, underwater cable arrays are subjected to external forces due to weight and buoyancy, and hydrodynamic forces, position-dependent, like drag forces. They depend upon both the orientation and depths of the cable segments and on depths of elemental devices, with the result that the Method of Imaginary Reactions is not entirely applicable to the cable structure we wish to deal with in this report.

This problem can be solved by combining the Method of Imaginary Reactions with the Method of Successive Approximations.[3] Using this combined technique, the equilibrium configuration for arbitrary current profiles can be generated to any desired degree of accuracy. Essentially, this combined technique consists of making an initial guess as to the values of the hydrodynamic forces and uses these values to find the equilibrium position of the structure by the Method of Imaginary Reactions. Once this position is found, the hydrodynamic forces are recalculated, and the position of the array under the new forces is again found by the imaginary reactions. This iterative procedure is continued until the equilibrium configuration has been obtained to within a specified accuracy.

One of the ways to find a measure of accuracy for the successive approximation routine is to compare the equilibrium coordinates of any cable station for two successive iterations. If the coordinates differ by less than a fixed amount, the iteration will be considered satisfied and if any coordinate change is greater than this fixed amount, the iteration is continued. Analytically, if COMPD denotes this fixed accuracy value, then the successive approximation routine is considered satisfied when

$$|\theta^{i}_{m,n} - \theta^{i-1}_{m,n}| \leq \text{COMPD} \tag{36,1}$$

for the main array where $\theta^i = x$, y or z represents the equilibrium coordinates of any cable station obtained from the (i)th successive approximation routine. Thus, the combined technique offers the advantage that it can be used for the position dependent forces. In the following sections, this technique has been used to analyze the problem of a redundant structure.

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*A brief discussion of elemental devices is made in Chapter III.

CHAPTER II

A NEAR-HORIZONTAL CABLE ELEMENT IN A MULTI-MOORED ARRAY

The major thrust of this investigation has been to study and analyze the tri-moored structure that has two of the cables connected by a horizontal cable. (This cable is called a tie leg in this report). A technique is developed in this report that enables the Method of Imaginary Reactions to be used for such a structure. More recently, Skop and O'Hara have extended the work reported herein to the general redundant structure.[12]

A. THE BASIC APPROACH

Let one first consider the two legs of a tri-moored buoy system, to which a tie leg has been attached. This structure, then, looks like an "A". The "A" structure can further be divided into two coupled parts: 1) the lambda (Λ) structure and, 2) the tie leg structure . Neglecting the bending stiffness of the cables, there are only two conditions of coupling between the lambda structure and tie leg.

1. The geometrical compatibility condition
2. The force balance condition

All that is required is a simple lambda structure subjected to the above constraints between (Λ) structure and tie leg, and then the structure will behave like an "A" structure.

B. THE GEOMETRICAL COMPATIBILITY CONDITION

Let one start with a lambda (Λ) structure having A as an apex and B and C as anchor points. (See Figure 6) Points D and E represent approximately the position at which one wishes a tie leg inserted in the

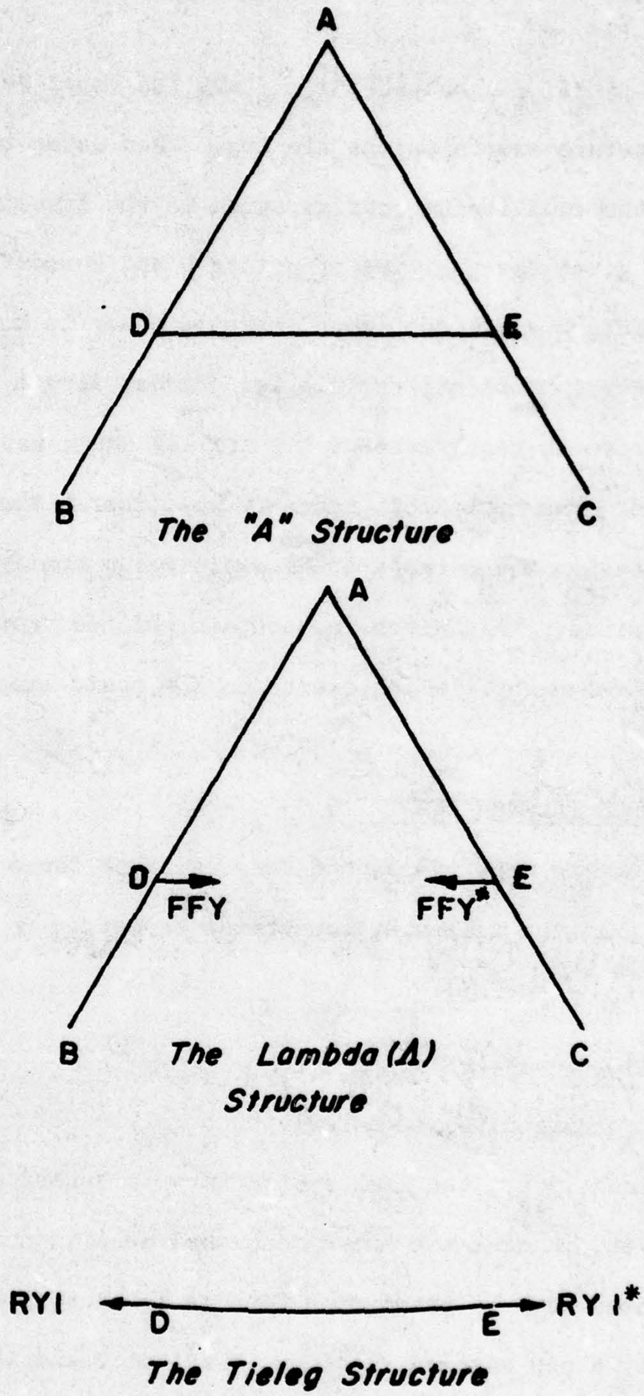


Figure 6 : Representation of the Basic Tie Leg Concept

structure. $(FFY)_{at\ D}$ and $(FFY^*)_{at\ E}$ are the total resultant forces that the lambda structure exerts on the tie leg. Then using the Method of Imaginary Reactions the equilibrium configuration of the structure is obtained which, in result, gives the position of points D and E under loads.

If points D and E are known, then in order to meet the geometrical compatibility constraint, the tie leg chordal length must fit these points. It is, therefore, required that the tie leg shall have these points as end constraints. The Method of Imaginary Reactions is then applied to the tie leg by releasing the E end and the equilibrium configuration of the tie leg is obtained. This gives one certain end reactions $(EY1)_{at\ D}$ and $(RY1^*)_{at\ E}$ which the tie leg exerts on the basic lambda structure at points D and E.

C. THE FORCE BALANCE CONDITION

In order to meet the second constraint of force balance, it is important that the following conditions be met:

$$-(RY1)_{at\ D} = (FFY)_{at\ D} \qquad (1,2a)$$

$$(RY1^*)_{at\ E} = -(FFY^*)_{at\ E} \qquad (1,2b)$$

When this condition has been met, the complete solution to the problem has been obtained, i.e., the lambda structure is behaving as an "A" structure.

However, in case the above mentioned condition is not met, then the whole process must be repeated. That is (FFY) at D and (FFY*) at E is replaced by a new assumed reaction (FFY)' at D and (FFY*)' at E and new positions of points D and E are found under the action of these forces. Then, these positions are taken as reference points for finding the equilibrium position of the tie leg, which gives one the end reaction. This process is repeated until the force balance condition has been met. Once this

happens the two constraints have been taken into consideration and the problem is solved.

To reduce the number of iterations so as to satisfy the above constraint rather quickly, a convergence algorithm is developed in Chapter IV. This algorithm utilizes the values of FFY and RY1, and if force balance constraint is not satisfied, the routine employs a technique by which a new value of FFY' ($FFY \gtrless FFY' \gtrless RY1$) and FFY*' ($FFY^* \gtrless FFY^{*\prime} \gtrless RY1^*$) are obtained. This and subsequent values of FFY' and FFY*' assure convergence to the correct values of forces, which satisfy the force balance condition, in minimum number of iterations.

CHAPTER III

MODELING AND ANALYSIS OF THE INTERNALLY REDUNDANT ARRAY SYSTEM

In this chapter, a brief description of the techniques used to model and analyze the array system is presented. The chapter has been divided into various sections, each of which deals with one phase of the modeling process. Further, each section deals separately with the main structure and the tie leg structure.

A. A FEW GUIDELINES

In this section a few guidelines for modeling the array are presented:

1. The tri-moored structure consists of a subsurface buoy, anchored to the bottom by three cables. These cables are referred to by number n where n = 1, 2 and 3. These cables are broken up into M(n) stations.
2. The primary anchor, the anchor for cable n = 1, is represented by (1,1). All other stations are referred to by subscript pair (m,n) where m = 2, 3, --M(n) and n = 1, 2, or 3 except for the secondary anchors which are referred to by (M(2),2) and (m(3),3). The branch point at the subsurface buoy, in this case, is represented by (M(1),1). This is the same point as (1,2) or (1,3) but by convention is represented by (M(1),1).
3. The tie leg is attached to cables 2 and 3, at stations (L,2) and (L,3) respectively where L is any station between 1 and M(n). The tie leg is further broken up into MN stations. Both arrays are represented diagrammatically as follows:

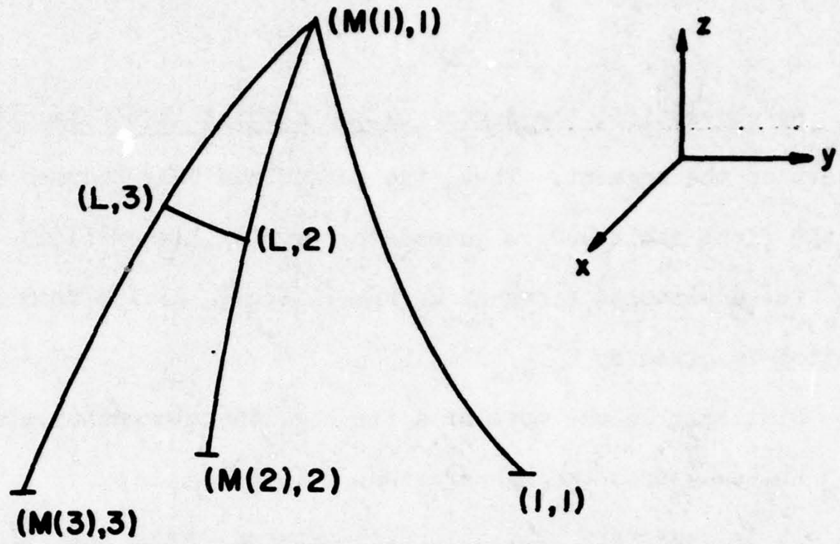


Figure 7: Nomenclature for the Tri-moored Array Structure with a Tie Leg

4. Since the external forces acting on the cables have to be lumped at these stations, each cable segment between the stations behaves like a straight line. The following guidelines are used for lumping these forces
   i. Each point of discontinuity in a physical property of a cable is represented by a different station. Thus, each cable in the array has constant physical properties.
   ii. As many additional stations are used as necessary to obtain a successful approximation to the continuous equilibrium shape of the array. However, the method of analysis does not depend upon the number stations and any ultrafine representation of the cable does not help.

B. DISCRETE ELEMENT NOMENCLATURE

The method of analysis has the ability to take into account discrete elements in the cable. These discrete elements exert a force on the system. The external forces, because of these elements, are lumped also at the stations neighboring them. Half segment lumping technique[5] is used here.

The objects which are attached to the (m,n)th cable segment on the main structure are indexed by (k,m,n) where k = 1,2 --- k(m,n), counting in the direction as shown in Figure 8. For the tie leg--the objects are indexed by (j,m) where j = 1, 2 --- j(m).

By convention, the device on the station itself becomes the last object on the segment. Thus, the subsurface buoy becomes the last device on the first cable and is indexed by (k(M(1),1)), M(1),1).

The unstressed distance of the $(k,m,n)_{th}$ device from the $(m,n)th$ station is given by $\bar{S}_{k,m,n}$

Similarly in the case of a tie leg, the element $(j,m)^{th}$ would be $\bar{S}_{j,m}$ ft, away from the m^{th} station.

It is necessary to distinguish between forces that are lumped at the lower segment from the forces that are lumped at the upper segment. Half segment technique[5] is used to lump these forces on the respective stations.

The objects that are attached to the half segment adjoining the $(m,n)th$ station would then be differentiated from the objects adjoining $(m+1,n)^{th}$ segment as follows:

Let k(m,n) represent the value of k such that

$$\bar{S}_{k,m,n} \leq B\bar{L}_{om,n}/2$$

for $k = 1,2 ---\bar{k}(m,n)$

$$\bar{S}_{k,m,n} > B\bar{L}_{om,n}/2$$

for $k = \bar{k}(m,n)+1, ---k(m,n)$

Similarly for a tie leg let j (m) represent the value of j such that

$$\bar{S}_{j,m} \leq L_m/2$$

and

for $j = 1,2 ---\bar{j}(m)$

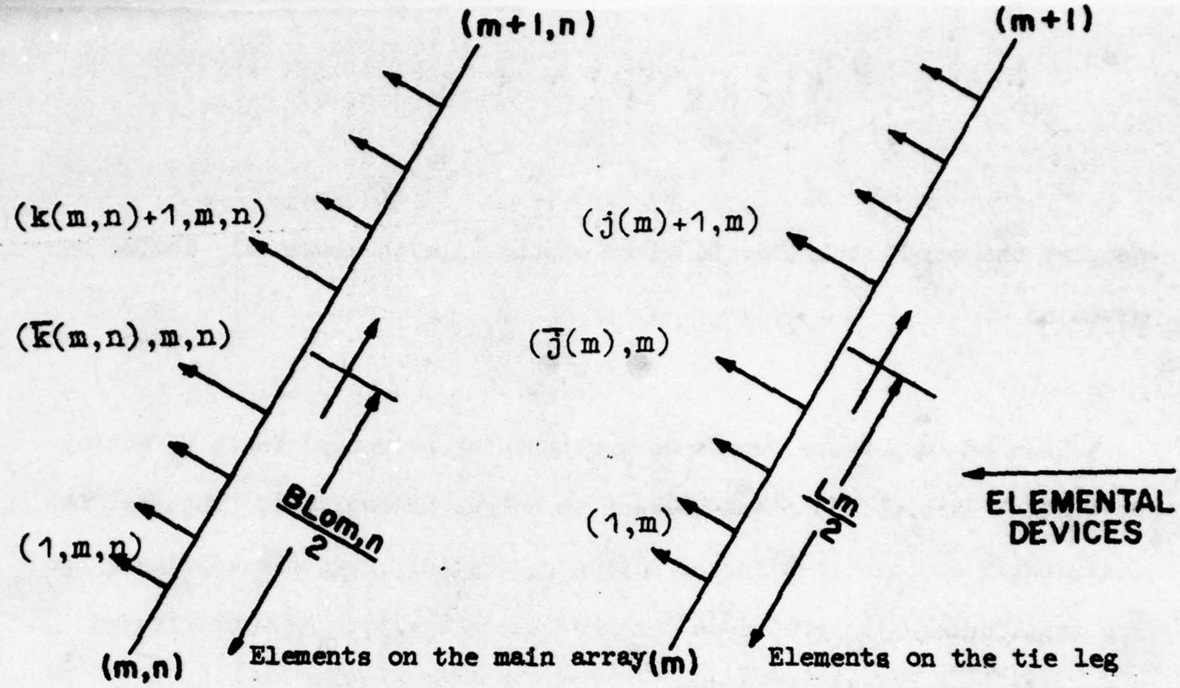


Figure 8: Representation of the Discrete Elemental Devices

These equations are diagrammatically represented by the figures shown above.

C. FORCES ACTING ON THE ARRAY SYSTEM

The total forces acting on the array system are made up of two factors:

1. The weight and buoyancy forces--here weight and buoyancy of discrete elements as well as of the cable are taken into account.
2. The hydrodynamic drag forces which are acting because of the interface between the cable and the current acting in water.

1. Weight and Buoyancy Forces

In this section only the effect of weight and buoyancy is considered.

The weight and buoyancy actually can be differentiated only by the direction in which they act. The weights act downwards and buoyancy acts upwards. The Z direction is considered positive upwards.

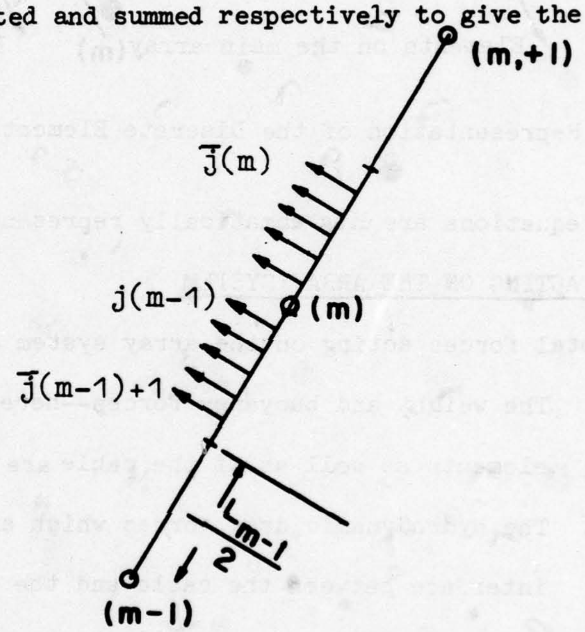
To compute the weight and buoyancy forces let the weight (or buoyancy) per unit length in water of the mth cable segment be given by

$$W_m^c$$

and let the weight buoyancy in water of the (j,m)th elemental device be given as

$$W^e_{j,m}$$

Then to lump these forces as a weight (or buoyancy) force W_m acting at the mth station, the half segment technique is employed. That is, the distributed and discrete forces acting on the half segments adjoining the mth stations are integrated and summed respectively to give the lumped forces at that station.



m = 2,3 ---MN-1

Figure 9: Representation of Lumped Force on a Station Using Half Segment Technique

Then because of the discrete element the weights that are lumped at station m, acting in the half segment of the (m-1) segment as shown in Figure 9 are expressed by

$$\sum_{j=\bar{J}(m-1)+L}^{j(m-1)} W^e_{j,m-1} \qquad (1,3)$$

Similarly the forces that are lumped at station m because of weights acting at the lower half segment of the mth segment are expressed by

$$\sum_{j=1}^{j=\bar{j}(m)} W^{e}_{j,m} \qquad (2,3)$$

Also, the lumped force at station mth because of the weight (buoyancy) of the cable would similarly be

$$\frac{1}{2} W^{c}_{m-1} L_{m-1} + \frac{1}{2} W^{c}_{m} L_{m} \qquad (3,3)$$

Such that total force lumped at mth station due to weights is given by

$$W_m = \sum_{j=\bar{j}(m-1)+1}^{j(m-1)} W^{e}_{j,m-1} + \sum_{j=1}^{\bar{j}(m)} W^{e}_{j,m}$$

$$+ \frac{1}{2} [W^{c}_{m-1} L_{m-1} + W^{c}_{m} L_{m}] \qquad (4,3)$$

Exactly the same discussion holds good for lumping the weights as forces in case of the tri-moored buoy structure. In this case, however, another factor n, the number of cables, has also to be taken into account.

Then for the tri-moored structure

$$W_{m,n} = \sum_{k=\bar{k}(m-1,n)+1}^{k(m-1,n)} W^{e}_{k,m-1,n} + \sum_{k=1}^{\bar{k}(m,n)} W^{e}_{k,m,n}$$

$$+\frac{1}{2} [W^{c}_{m-1,n} \; BL_{o\,m-1,n} + W^{c}_{m,n} \; BL_{o\,m,n}]$$

Where
m = 2,3,4---M(n)-1.

n = 1,2,3. (5,3)

and for m = M(1) n = 1, the subsurface buoy

$$W_{M(1),1} = \sum_{k=\bar{k}(M(1),1)+1}^{k(M(1),1)} W^{e}_{k,M(1),1} + \sum_{k=1}^{\bar{k}(2,2)} W^{e}_{k,2,2} + \sum_{k=1}^{\bar{k}(2,3)} W^{e}_{k,2,3} + \frac{1}{2}\left[W^{c}_{M(1),1}\, BL_{oM(1),1} + W^{c}_{1,2}\, BL_{o1,2} + W^{c}_{1,3}\, BL_{o1,3}\right] \qquad (6,3)$$

which are various expressions for representing the weights as lumped forces on the stations. In deriving this expression, however, the density of the water has been assumed to be constant.

2. Modeling of a Current Profile

Weight and buoyancy forces are one type of external forces. There are additional external forces which act on the cable because of the hydrodynamic interaction between the cable and an ocean current. This interaction produces drag forces which are dependent upon the velocity and direction of the local ocean current i.e., the angle at which local ocean current attacks the cable.

The method of analysis developed herein makes no restrictions on the shape of the current profile. For the sake of convenience, however, the following assumptions are made:

1. The ocean current, though depth dependent in magnitude, is uni-directional and normal to the direction of gravity.
2. The drag force component which acts in the direction normal to both the stream and the cable is zero.

The first assumption is made because most design currents are given as depth dependent and uni-directional. The second assumption is made because

of the limited experimental data available to support a general analytic expression for the side component of "drag" on cables.

The first assumption dictates that the current possess no Z component. If the angular direction with respect to the x axis is denoted by ϕ, the expression for current in general can be written as

$$\vec{V} = V(Z) \; [\; \vec{i} \; \mathrm{Cos} \; \phi + \vec{j} \; \mathrm{Sin} \; \phi] \qquad (7,3)$$

Where

$V(Z)$ = Magnitude of current profile at a height Z above the deepest anchor ($Z=o$).

$\vec{i}$ = Unit vector in x direction

$\vec{j}$ = Unit vector in y direction

3. Hydrodynamic Coordinates

In order to calculate the various drag forces acting on the system, it is convenient to transform into a new set of natural hydrodynamic coordinates, defined with respect to direction of the cable and the current.

The following analysis is presented for the tri-moored structure. However, the same approach is used for the tie leg array.

1. In order to find a natural hydrodynamic coordinate system, we proceed in the following manner:

   i. Let $\tau_{m,n}$ be the unit tangent to the (m,n)th cable segment, considered positive in the dir^n of increasing m

   ii. Then

$$\pi_{m,n} = \frac{\vec{V} \times \tau m,n}{|\pi_{m,n}|} \qquad (8,3)$$

   where $\pi m,n$ is a unit vector normal to both the (m,n)th cable segment and the current and

   iii. $\eta \; m,n = \tau m,n \times \pi m,n$ is a unit vector normal to the cable and lying in the plane that includes the (m,n)th cable segment and the stream.

In order to express the hydrodynamic base reference in terms of basic x, y, z reference frame, we obtain the following relation:

2. The unit vector $\tau m,n$ is expressed in terms of

$$\tau_{m,n} = \alpha_{m,n} \vec{i} + \beta_{m,n} \vec{j} + \gamma_{m,n} \vec{k} \qquad (9,3)$$

where $\alpha_{m,n}$ $\beta_{m,n}$ and $\gamma_{m,n}$ are the dir^n cosines of the (m,n)th cable segment defined by

$$\alpha m,n = \frac{X_{m+1,n} - X_{m,n}}{BL_{m,n}} \qquad (10,3a)$$

$$\beta m,n = \frac{Y_{m+1,n} - Y_{m,n}}{BL_{m,n}} \qquad (10,3b)$$

$$\gamma m,n = \frac{Z_{m+1,n} - Z_{m,n}}{BL_{m,n}} \qquad (10,3c)$$

3. To express $\pi m,n$ in terms of basic x,y,z coordinates we proceed as follows:

$$\pi m,n = \frac{\vec{V} \chi \tau m,n}{|\pi m,n|}$$

and

$$\vec{V} x \tau m,n = V(z)[\vec{i} \text{ Cos } \phi + \vec{j} \text{ Sin } \phi] \text{ x } [\alpha m,n \vec{i} + \beta m,n \vec{j} + \gamma m,n \vec{k}]$$

$$= V(Z) \begin{vmatrix} \vec{i} & \vec{j} & \vec{k} \\ \text{Cos } \phi & \text{Sin } \phi & 0 \\ \alpha m,n & \beta m,n & \gamma m,n \end{vmatrix}$$

$$= V(Z)[\vec{i} (\gamma m,n \text{ Sin } \phi) - \vec{j} (\gamma m,n \text{ Cos } \phi) + \vec{k} (\beta m,n \text{ Cos } \phi - \alpha m,n \text{ Sin } \phi)]$$

Also $\left|\vec{V} \times \tau_{m,n}\right| = \left|\vec{V}\right| \left|\tau_{m,n}\right| \Delta_{m,n}$

Where

$\Delta_{m,n}$ is the sine of the angle between the (m,n)th cable segment and the stream and is given by

$$\Delta_{m,n} = \sqrt{\gamma_{m,n}^2 + (\beta_{m,n} \text{ Cos } \phi - \alpha_{m,n} \text{ Sin } \phi)^2}$$

Also

$$\left|\vec{V}\right| = V(Z)$$

And

$$\left|\tau_{m,n}\right| = \sqrt{\alpha_{n,m}^2 + \beta_{m,n}^2 + \gamma_{m,n}^2} = 1$$

Thus

$$\pi_{m,n} = \frac{1}{\Delta_{m,n}} \{\vec{i}(\gamma_{m,n} \text{ Sin } \phi) - \vec{j}\,(\gamma_{m,n} \text{ Cos } \phi)$$

$$+\vec{k}(\beta_{m,n} \text{ Cos } \phi - \alpha_{m,n} \text{ Sin } \phi)\} \qquad (11,3)$$

4. Similarly to express $\eta_{m,n} = \pi_{m,n} \times \tau_{m,n}$ we proceed in the above manner to get

$$\eta_{m,n} = \frac{1}{\Delta_{m,n}} \{[(\gamma_{m,n}^2 + \beta_{m,n}^2) \text{ Cos } \phi - \alpha_{m,n}\, \beta_{m,n} \text{ Sin}\phi]\, \vec{i}$$

$$+[(\gamma_{m,n}^2 + \alpha_{m,n}^2) \text{ Sin}\phi - \alpha_{m,n}\beta_{m,n} \text{Cos}\phi]\, \vec{j}$$

$$-[\gamma_{m,n}\, \beta_{m,n} \text{ Sin}\phi + \gamma_{m,n}\, \alpha_{m,n} \text{ Cos}\phi]\, \vec{k}\}$$

4. <u>Hydrodynamic Coordinates for the Tie Leg</u>

The tie leg is a single cable and as such, does not involve an index n, with the results the expressions (10,3), (11,3) and (12,3) are valid if

the index (n) is removed.

Thus the transformation expressions for hydrodynamic coordinates in case of a tie leg would be expressed as:

$$\tau_m = \alpha_m \vec{i} + \beta_m \vec{j} + \gamma_m \vec{k} \quad (13,3)$$

$$\pi_m = \frac{1}{\Delta_m} [\vec{i}(\gamma_m \text{Sin}\phi) - \vec{j}(\gamma_m \text{Cos}\phi)$$

$$+ \vec{k}(\beta_m \text{Cos}\phi - \alpha_m \text{Sin}\,\phi)] \quad (14,3)$$

$$\eta_m = \frac{1}{\Delta_m} [\{(\gamma_m^2 + \beta_m^2) \text{Cos}\,\phi - \alpha_m \beta_m \text{Sin}\,\phi)\} \vec{i}$$

$$+ (\gamma_m^2 + \alpha_m^2) \text{Sin}\phi - \alpha_m \beta_m \text{Cos}\phi\} \vec{j}$$

$$-\{\gamma_m \beta_m \text{Sin}\,\phi + \gamma_m \alpha_m \text{Cos}\,\phi\} \vec{k}] \quad (15,3)$$

5. The Hydrodynamic Distributed Forces

Once a set of hydrodynamic coordinates has been obtained, it becomes a simple matter to represent the hydrodynamic forces for unit length which are then resolved into τ, π and η directions.

a) Side Force in the π Direction

Pode has demonstrated some inherent difficulties that exist in defining hydrodynamic force.(6) Limited data is available to determine the functional forms of a side force in the π direction. However, it is known that magnitude of this force compared with the other two components is small and as such is neglected.(9)

Also $\left|\vec{V} \times \tau_{m,n}\right| = \left|\vec{V}\right| \left|\tau_{m,n}\right| \Delta_{m,n}$

Where

$\Delta_{m,n}$ is the sine of the angle between the (m,n)th cable segment and the stream and is given by

$$\Delta_{m,n} = \sqrt{\gamma^2_{m,n} + (\beta_{m,n} \text{ Cos } \phi - \alpha_{m,n} \text{ Sin } \phi)^2}$$

Also

$$\left|\vec{V}\right| = V(Z)$$

And

$$\left|\tau_{m,n}\right| = \sqrt{\alpha^2_{n,m} + \beta^2_{m,n} + \gamma^2_{m,n}} = 1$$

Thus

$$\pi_{m,n} = \frac{1}{\Delta_{m,n}} \{\vec{i}(\gamma_{m,n} \text{ Sin } \phi) - \vec{j}\,(\gamma_{m,n} \text{ Cos } \phi)$$

$$+\vec{k}(\beta_{m,n} \text{ Cos } \phi - \alpha_{m,n} \text{ Sin } \phi)\} \qquad (11,3)$$

4. Similarly to express $\eta_{m,n} = \pi_{m,n} \times \tau_{m,n}$ we proceed in the above manner to get

$$\eta_{m,n} = \frac{1}{\Delta_{m,n}} \{[(\gamma^2_{m,n} + \beta^2_{m,n}) \text{ Cos } \phi - \alpha_{m,n}\, \beta_{m,n} \text{ Sin}\phi]\, \vec{i}$$

$$+[(\gamma^2_{m,n} + \alpha^2_{m,n}) \text{ Sin}\phi - \alpha_{m,n}\beta_{m,n} \text{Cos}\phi]\, \vec{j}$$

$$-[\gamma_{m,n}\, \beta_{m,n} \text{ Sin}\phi + \gamma_{m,n}\, \alpha_{m,n} \text{ Cos}\phi]\, \vec{k}\}$$

4. <u>Hydrodynamic Coordinates for the Tie Leg</u>

The tie leg is a single cable and as such, does not involve an index n, with the results the expressions (10,3), (11,3) and (12,3) are valid if

b) Normal Drag Force in η Directions

It is known that the normal drag force for unit length which acts in the η direction has a magnitude given by

$$f^{\eta}_{m,n} = \frac{\rho}{2} C^{N}_{m,n} \, d_{m,n} \, (\vec{V}.\eta_{m,n})^{2} \qquad (16,3a)$$

where

ρ = the density of the fluid

$C^{N}_{m,n}$ = the coefficient of drag of (m,n)th cable segment

d_{mn} = the diameter of (m,n)th cable segment

Expression for normal drag force in η direction for the tie leg array is essentially the same as (16,3a) except that no index n exists and as such is given by

$$f^{\eta}_{m} = \frac{\rho}{2} C^{N}_{m} \, d_{m} \, (\vec{V}.\eta_{m})^{2} \qquad (16,3b)$$

where C^{N}_{m} is the coefficient of drag of m th cable segment, the segment being normal to stream and d_m is the diameter of the mth cable segment.

c) Tangential Drag Force in τ Direction

In most of the work done, this component is neglected being made equal to zero. However, as suggested by Skop and Kaplan,[9] this analysis assumes that this force can be given by the expression

$$f^{\tau}_{m,n} = \frac{\rho}{2} C^{P}_{m,n} \, d_{m,n} \, V(Z) \, [\vec{V}.\tau_{m,n}] \qquad (17,3a)$$

where

$C^{P}_{m,n}$ = the coefficient of drag of (m,n)th cable segment when the segment is parallel to the stream.

Similarly the tangential drag force for the tie leg is given by:

$$f^{\tau}_{m} = \frac{\rho}{2} C^{P}_{m} \, d_{m} \, V(Z) \, [\vec{V}. \tau_{m}] \qquad (17,3b)$$

where C^P_m is coefficient of drag of m^th^ cable segment when the segment is parallel to the stream.

6. The Total Hydrodynamic Force

From the above expressions, then, it becomes clear that the hydrodynamic force per unit length which is acting on the (m,n)th cable segment can be written as:

$$f^T_{m,n} = f^\eta_{m,n}\ \eta_{m,n} + f^\tau_{m,n}\ \tau_{m,n} \tag{18,3}$$

where

$$f^\eta_{m,n} = \frac{\rho}{2} C^N_{m,n}\ d_{m,n}\ (V(Z)\Delta_{m,n})^2$$

$$= \mu^c_{m,n}\ \Delta^2_{m,n}\ V^2(Z) \tag{19,3}$$

and

$$\mu^c_{m,n} = \frac{\rho}{2} C^N_{m,n}\ d_{m,n} \tag{20,3}$$

also

$$f^\tau_{m,n} = \frac{\rho}{2} C^P_{m,n}\ d_{m,n}\ V(Z)\ [\vec{V}.\tau_{m,n}]$$

$$= \mu^c_{m,n}\ r^D_{m,n}\ V^2(Z)[\alpha_{m,n}\ \mathrm{Cos}\ \phi + \beta_{m,n} \mathrm{Sin}\phi] \tag{21,3}$$

where

$$r^D_{m,n} = \frac{C^P_{m,n}}{C^N_{m,n}} \tag{22,3}$$

Thus having known the expressions for $f^\eta\ m,n$ and $f^\tau\ m,n$ - these can be substituted into the equation (18,3) to get the total hydrodynamic force. Similarly, the expression for total hydrodynamic force in the case of a tie leg

is given by

$$f_m^{Total} = f_m^{\eta}\, \eta_m + f_m^{\tau}\, \tau_m \qquad (23,3)$$

where f_m^{τ} and f_m^{η} are similar to Eqs. (21,3) and (19,3) with no (n).

To derive expressions for the projection of these hydrodynamic force in the i, j and k dir^n, we proceed as follows:

The hydrodynamic force for the tri-moored structure acting in the α dir^n is given by

$$h_{m,n}^{c:x} = C_{m,n}^{c:x} \quad v^2(Z) \qquad (23,3a)$$

Similarly

$$h_{m,n}^{c:y} = C_{m,n}^{c:y} \quad v^2(Z) \qquad (23,3b)$$

$$h_{m,n}^{c:z} = C_{m,n}^{c:z} \quad v^2(Z) \qquad (23,3c)$$

and for the tie leg by

$$h_{m}^{c:x} = C_{m}^{c:x} \quad v^2(Z) \qquad (24,3a)$$

$$h_{m}^{c:y} = C_{m}^{c:y} \quad v^2(Z) \qquad (24,3b)$$

$$h_{m}^{c:y} = C_{m}^{c:y} \quad v^2(Z) \qquad (24,3c)$$

where C m,n's are known as the drag constants and they are defined by:

$$C_{m,n}^{c:x} = \mu_{m,n}^{c} \, [\Delta_{m,n} \, (\gamma_{m,n}^{2} + \beta_{m,n}^{2}) \, \mathrm{Cos}\, \phi \; -$$

$$\Delta_{m,n} \, \alpha m,n \; \beta_{m,n} \; \mathrm{Sin}\, \phi \; +$$

$$r_{m,n}^{D} \, (\alpha_{m,n} \, \mathrm{Cos}\phi + \beta_{m,n} \, \mathrm{Sin}\phi) \; \alpha \; m,n] \qquad (25,3a)$$

and

$$C^{c:y}_{m,n} = \mu^{c}_{m,n} [\Delta_{m,n}(\gamma^{2}_{m,n} + \alpha^{2}_{m,n}) \operatorname{Sin}\phi -$$

$$\Delta_{m,n} \alpha_{m,n} \beta_{m,n} \operatorname{Cos}\phi +$$

$$r^{D}_{m,n} (\alpha_{m,n} \operatorname{Cos}\phi + \beta_{m,n} \operatorname{Sin}\phi)\beta_{m,n}] \tag{25,3b}$$

$$C^{c:z}_{m,n} = \mu^{c}_{m,n}[-\Delta_{m,n} (\alpha_{m,n} \operatorname{Cos}\phi + \beta_{m,n} \operatorname{Sin}\phi) \gamma m,n$$

$$+ r^{D}_{m,n}(\alpha_{m,n} \operatorname{Cos}\phi + \beta_{m,n} \operatorname{Sin}\phi)\gamma m,n] \tag{25,3c}$$

similarly for the tie leg

$$C^{c:x}_{m} = \mu^{c}_{m}[\Delta_{m}(\gamma^{2}_{m} + \beta^{2}_{m}) \operatorname{Cos} \phi -\Delta_{m} \alpha_{m} \beta_{m} \operatorname{Sin} \phi +$$

$$r^{D}_{m} (\alpha_{m} \operatorname{Cos}\phi +\beta_{m} \operatorname{Sin}\phi)\alpha m] \tag{26,3a}$$

$$C^{c:y}_{m} = \mu^{c}_{m}[\Delta_{m} (\gamma^{2}_{m} + \alpha^{2}_{m}) \operatorname{Sin} \phi -\Delta_{m} \alpha_{m} \beta_{m} \operatorname{Cos} \phi +$$

$$r^{D}_{m} (\alpha_{m} \operatorname{Cos}\phi +\beta_{m} \operatorname{Sin}\phi)\beta_{m}] \tag{26,3b}$$

and

$$C^{c:z}_{m} = \mu^{c}_{m}[-\Delta_{m} (\alpha_{m} \operatorname{Cos}\phi+\beta_{m} \operatorname{Sin}\phi)\gamma_{m} + r^{D}_{m}$$

$$(\alpha_{m} \operatorname{Cos}\phi + \beta_{m} \operatorname{Sin} \phi)\gamma_{m}] \tag{26,3c}$$

Once the hydrodynamic force on the cable array is found, the next stage is to lump these forces on the stations. To lump the distributed forces as a single force which acts at the (m,n)th cable station, the half segment lumping technique (5) is employed. Then using this technique, the lumped hydrodynamic forces are given by the equations:

for $m = 2,3 --- M(n)-1 \quad n = 1,2,3$

$$H^{c:\theta}_{m,n} = C^{c:\theta}_{m,n} \overline{V} (m,n: \ BL_{m,n/2}, BL_{m,n}) +$$

$$C^{c:\theta}_{m+1,n} \overline{V} (m+1,n: 0, BL_{m+1,n/2}) \qquad (27,3)$$

and for $m = M(1)$ and $n = 1$

$$H^{c:\theta}_{M(1),1} = C^{c:\theta}_{M(1),1} \overline{V} (M(1),1: \ BL_{M(1),1/2}, BL_{M(1),1})$$

$$+ \ C^{c:\theta}_{1,2} \overline{V} (1,2: \ 0, BL_{1,2/2})$$

$$+ \ C^{c:\theta}_{1,3} \overline{V} (1,2: \ 0, BL_{1,3/2}) \qquad (28,3)$$

where $\theta = x,y$ or z

The function $\overline{V} (m,n,\Xi_1,\Xi_2)$ represents the integral of $(V^2(Z))$ along the (m,n)th half segment and is represented by

$$\overline{V} (m,n,\Xi_1,\Xi_2) = \int_{\Xi 1}^{\Xi_2} v^2[Z(m,n:\xi)]d\xi \qquad (29,3)$$

where the argument z of $V^2(Z)$ is expressed in terms of the integration parameter ξ along the (m,n)th cable segment through the relation

$$Z = Z (m,n:\xi) = Z_{m,n} + \gamma_{m+1,n} \qquad (30,3)$$

where $\gamma_{m+1,n}$ is the direction cosine of the mth segment as defined by equation (10,3c).

In the case of a tie leg the half segment technique yields the lumped hydrodynamic forces given by the following expression:

for m = 2,3 ---MN-1

$$H_m^{c:\theta} = C_m^{c:\theta}\ \overline{V}\ (m:B_{m/2}, B_m) +$$

$$C_{m+1}^{c:\theta}\ \overline{V}\ (m+1:\ 0,\ B_{m+1}) \qquad (31,3)$$

where θ = x, y or z

and expression V (m,Ξ1,Ξ2) represents the integral of $V^2(z)$ along the mth half segment and is represented by

$$\overline{V}\ (m,\Xi_1, \Xi_2) = \int_{\Xi_1}^{\Xi_2} V^2\ [Z(m,\xi)]\ d\xi \qquad (32,3)$$

D. DISCRETE ELEMENT HYDRODYNAMIC FORCES

The direction of drag on the discrete elements becomes parallel to V if it is assumed that there is no lift associated with them. The magnitude of the drag force in that case is given by:

$$\frac{\rho}{2}\, C^D_{k,m,n}\ A_{k,m,n}\ V^2(Z) \qquad (33,3)$$

where

$C^D_{k,m,n}$ = coefficient of drag of the (k,m,n)th elemental device

$A_{k,m,n}$ = effective cross-sectional area of (k,m,n)th elemental device

Then if this force be resolved in x, y and z coordinate system, the hydrodynamic force due to the (k,m,n)th elemental device is found as:

$$h^{e:x}_{k,m,n} = C^{e:x}_{k,m,n}\ V^2(Z) \qquad (34,3a)$$

$$h^{e:y}_{k,m,n} = C^{e:y}_{k,m,n}\ V^2(Z) \qquad (34,3b)$$

$$h^{e:z}_{k,m,n} = 0 \qquad (34,3c)$$

where the drag constants of the (k,m,n)th elemental device are given by

$$C^{e:x}_{k,m,n} = \mu^e_{k,m,n} \mathrm{Cos}\phi \qquad (35,3a)$$

$$C^{e:y}_{k,m,n} = \mu^{e}_{k,m,n} \mathrm{Sin}\phi \tag{35,3b}$$

and $\mu^{e}_{k,m,n}$ being the hydrodynamic coordinate is defined by

$$\mu^{e}_{k,m,n} = \frac{\rho}{2} C^{D}_{k,m,n} A_{k,m,n} \tag{36,3}$$

Similarly, for the tie leg the hydrodynamic force due to the (j,m)th elemental device is given as

$$h^{e:x}_{j,m} = C^{e:x}_{j,m} V^2(Z) \tag{37,3a}$$

$$h^{e:y}_{j,m} = C^{e:y}_{j,m} V^2(Z) \tag{37,3b}$$

$$h^{e:z}_{j,m} = 0 \tag{37,3c}$$

where drag constants of the (j,m)th elemental device are given by

$$C^{e:x}_{j,m} = \mu^{e}_{j,m} \mathrm{Cos}\phi \tag{38,3a}$$

$$C^{e:y}_{j,m} = \mu^{e}_{j,m} \mathrm{Sin}\phi \tag{38,3b}$$

and $\mu^{e}_{j,m}$ is the hydrodynamic coordinate defined by

$$\mu^{e}_{j,m} = \frac{\rho}{2} C^{\ D}_{j,m} A_{m,n} \tag{39,3}$$

The next step is to apply the half segment lumping technique to find the hydrodynamic forces acting at the (m,n)th station and due to discrete elemental devices. This is given through the following relations:

for m = 2,3 ...M(n) - 1 and n = 1,2,3

$$H^{e:\theta}_{m,n} = \sum_{k=\bar{k}(m,n)+1}^{k(m,n)} C^{E:\theta}_{k,m,n} V^2 [Z(m,n:S_{k,m,n})] +$$

$$\sum_{k=1}^{\bar{k}(m+1,n)} C^{e:\theta}_{k,m+1,n} V^2[Z(m+1,n:S_{k,m+1,n})] \tag{40,3}$$

where θ = x, y or z

and for m = M(1) and n = 1

$$H^{e:\theta}_{M(1),1} = \sum_{k=\bar{k}(M(1),1)+1}^{k(M(1),1)} C^{e:\theta}_{k,M(1),1} V^2[Z(M(1),1:S_{k,m(1),1})]$$

$$+ \sum_{k=1}^{\bar{k}(1,2)} C^{e:\theta}_{k,1,2} V^2 [Z(1,2:S_{k,1,2})]$$

$$+ \sum_{k=1}^{\bar{k}(1,3)} C^{e:\theta}_{k,1,3} V^2 [Z(1,3:S_{k,1,3})] \tag{41,3}$$

Again, θ = x, y or z and argument z of $(V^2(Z))$ is expressed in terms of the position of the (k,m,n), the device along the (m,n)th segment through the relation

$$Z(m,n: S_{k,m,n}) = Z_{m-1,n} + \gamma_{m,n} S_{k,m,n} \tag{42,3}$$

Using half segment technique to find hydrodynamic forces acting at the mth station of the tie leg due to discrete elements, the following expression is derived:

$$H^{e:\theta}_{m} = \sum_{j=\bar{J}(m)+1}^{J(m)} C^{e:\theta}_{j,m} [V^2 Z(m,S_{j,m})]$$

$$+ \sum_{j=1}^{\bar{J}(m+1)} C^{e:\theta}_{j,m+1} V^2 [Z(m+1, S_{j,m+1})] \tag{43,3}$$

for m + 2,3 ---MN-1

where θ = x, y or z

E. FINAL EXTERNAL FORCES

Thus, to summarize the external force

$$(F^x_{m,n}, F^y_{m,n}, F^z_{m,n})$$

that is acting at the (m,n)th cable station for the tri-moored array can be given

as:

$$F^{x}_{m,n} = H^{c;x}_{m,n} + H^{e;x}_{m,n} \tag{44,3a}$$

$$F^{y}_{m,n} = H^{c;y}_{m,n} + H^{e;y}_{m,n} \tag{44,3b}$$

and

$$F^{z}_{m,n} = W_{m,n} + H^{e;z}_{m,n} \tag{44,3c}$$

Where the lumped weight forces $W_{m,n}$ are defined by Eqs. (5,3), the lumped hydrodynamic forces $H^{c;\theta}_{m,n}$ due to drag forces on the cable segments are defined by Eqs. (27,3), and the lumped hydrodynamic forces $H^{e;\theta}_{m,n}$ due to the drag forces on the elemental devices are defined by Eqs. (40,3). The above equations, however, do not apply to stations (M(2),2) and (M(3),3) as imaginary reactions act on these.

Similarly, the external force

$$(F^{x}_{m}, F^{y}_{m}, F^{z}_{m})$$

acting at the m th cable station for the tie leg array can be given by the following equations:

$$F^{x}_{m} = H^{c;x}_{m} + H^{e;x}_{m} \tag{45,3a}$$

$$F^{y}_{m} = H^{c;y}_{m} + H^{e;x}_{m} \tag{45,3b}$$

and

$$F^{z}_{m} = W_{m} + H^{e;z}_{m} \tag{45,3c}$$

Where W_m is defined by Eqs. (4,3), $H^{c;\theta}_{m}$ is defined by Eqs. (31,3) and $H^{e;\theta}_{m}$ is defined by Eqs. (43,3).

In the above equations, only the weight forces are constant. The hydrodynamic forces depend on the position of the structure through both the orientation and the depth. As discussed in Chapter I, this problem is solved by using the Method of Imaginary Reactions in conjunction with the Method of Successive Approximations.

CHAPTER IV

THE CONVERGENCE ALGORITHM USING A BINARY SEARCH ROUTINE

In Chapter II it was suggested that a convergence algorithm is required to satisfy the force balance condition using a near-minimum number of subroutine iterations. The force balance constraints suggest that in order to obtain the tie leg effect in a lambda structure (refer to Fig. 6) the following equations must be satisfied.

$$FFY_{\text{at D}} = -RY1_{\text{at D}} \tag{1,4a}$$

$$-FFY^*_{\text{at E}} = RY1^*_{\text{at E}} \tag{1,4b}$$

where FFY and FFY* are the resultant forces exerted by the main cable arrays on the tie leg and RY1 and RY1* are the end reactions that the tie leg exerts on the main cable array.

If the above set of forces do not satisfy the force balance constraints, then a different value for FFY and FFY* is used which produces a different chordal distance D'E' such that the tie leg fits into this new distance. Now, the force balance test is applied and if it is not satisfied, the above process is repeated.

This chapter discusses a technique which determines a new value for forces FFY and FFY* so that the number of iterations, before forces converge to satisfy equations (1,4), is hopefully made minimal. The following discussion is restricted to force FFY and reaction RY1; however, the same discussion holds for force FFY* and reaction RY1*.

Various algorithms to find a new value of FFY (refer to Figure 6) were evaluated; however, a Binary Search Routine was found to be the most direct method to achieve fact convergence.

A. BINARY SEARCH ROUTINE

A Binary Search Routine is an algorithm used to find a new value of FFY such that it always lies in between the previous two values of FFY and RY1. If the force FFY produces a reaction RY1 in the tie leg, then the new value of FFY is given by:

$$FFY' = ABS\left|\frac{ABS|RY1| - ABS|FFY|}{2}\right| + \text{Minimum}\,(ABS|FFY|, ABS|RY1|) \qquad (2,4)$$

This new value of FFY as given by FFY' and used with the proper sign on the tri-moored array, then, produces another value of RY1. The force balance criterion is applied and the process repeated until the condition is satisfied. A typical plot of the result of using this algorithm in a practical problem is as shown in Figure 10, where the convergence can be seen.

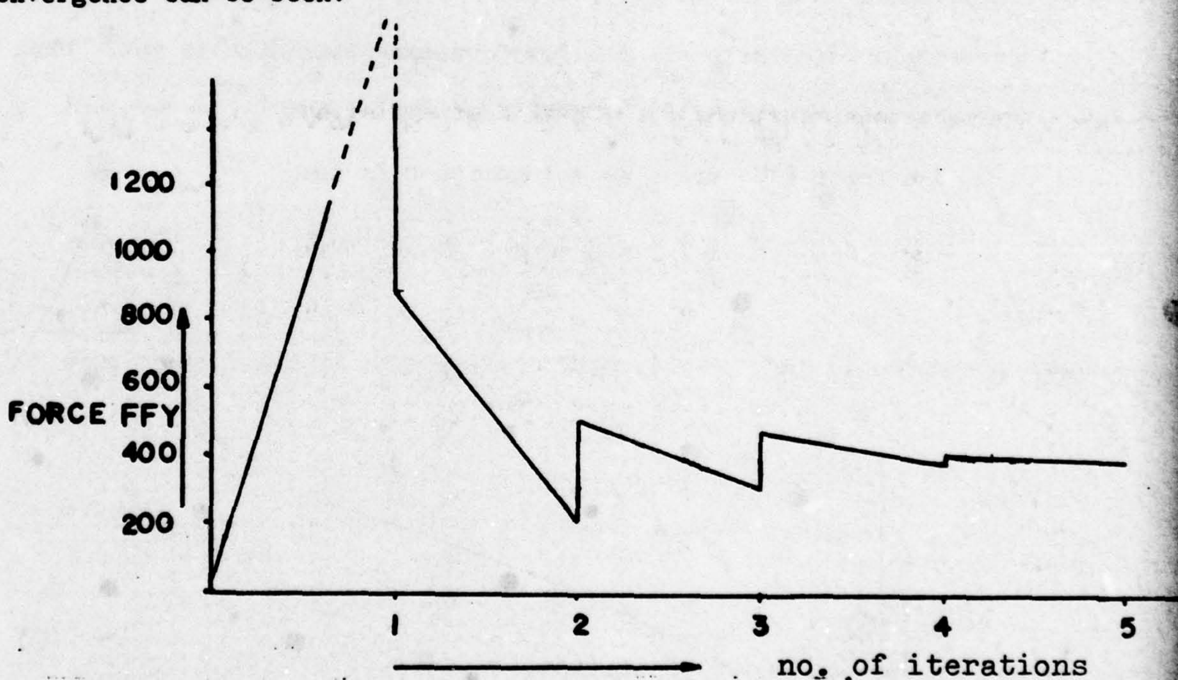


Figure 10: The Behavior of the Force FFY When Binary Search Routine Is Used

The details of the Binary Search Routine as used in the problem are listed below.

If FFY is the first assumed force that is applied on the main cable, then after equilibrium has been attained, a chordal length into which the tie leg is to fit is obtained. If this equilibrium configuration of the main structure is not compatible for the tie leg, then another assumed value FFY' (FFY' > FFY) is used on the main cable which reduces the chordal distance by an amount X (see Figure 11).

Thus by several iterations a tie leg is made to fit into an appropriately adjusted chordal distance, as shown in Figure 12. This produces a reaction RY1 in the tie leg. Now the force balance test is applied and if it is not satisfied, a new value of FFY"($FFY' \gtrless FFY'' \gtrless RY1$) is obtained from the Binary Search Routine using equation (2,4). This process is repeated until the force balance condition is met. When this happens equations (1,4) have been satisfied.

The force FFY, drawn as a function of x is:

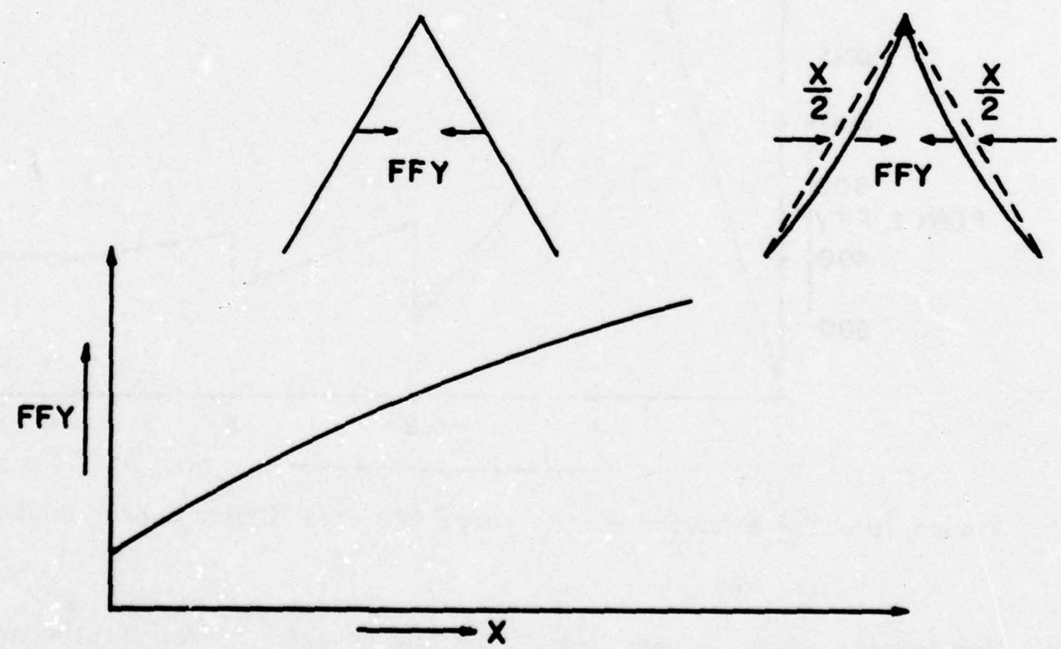


Figure 11: The Relationship Between the Force FFY and a Displacement X.

Similarly if a curve of reaction RY1 is drawn with respect to X, it will behave as shown below:

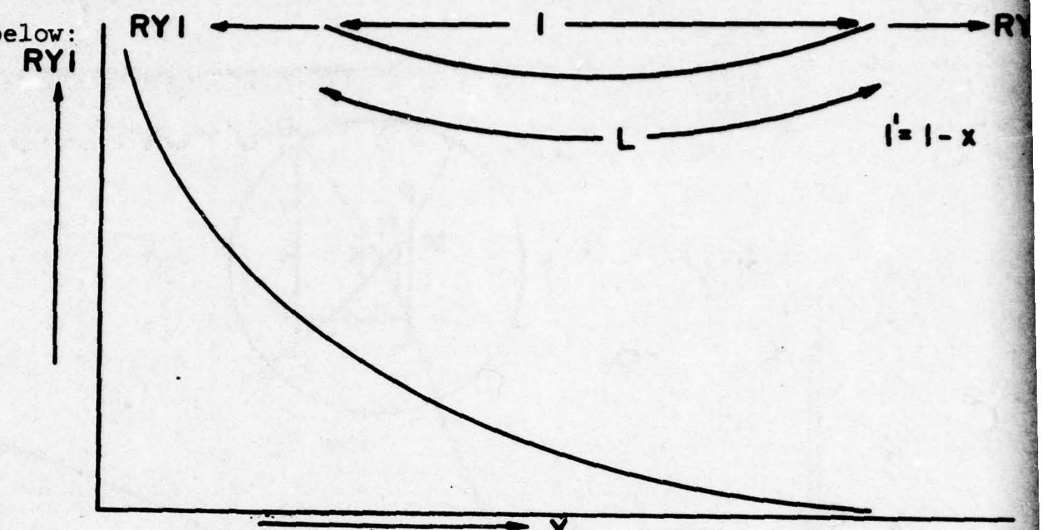


Figure 12: The Relationship Between the Reaction RY1 and a Displacement X.

If both these curves are superimposed, a graph as shown in Figure 13 is obtained.

Then to summarize, FFY' produces the reaction RY1 and this is represented by AB (notation follows Figure 13). Using binary search a new value of FFY is found and is represented by CD. Force FFY at D produces a reaction RY1 given by E so that this case is represented by DE. Binary Search Routine is used again to find the new value of FFY represented by FL.

Force represented by FL is used to find the chordal distance in which the tie leg has to fit. A reaction represented by point P is required to do so. The Binary Search Routine is again used to find a new value for force FFY, which is now represented by MN. Thus, this process is repeated until the forces represented by point K are obtained. At this stage equations (1,4) are satisfied. The convergence to the required forces that satisfy the force balance condition, in all computer runs and tests made, appears to be very quick.

A block diagram representing the stepwise use of the Binary Search Routine is shown in Figure 14.

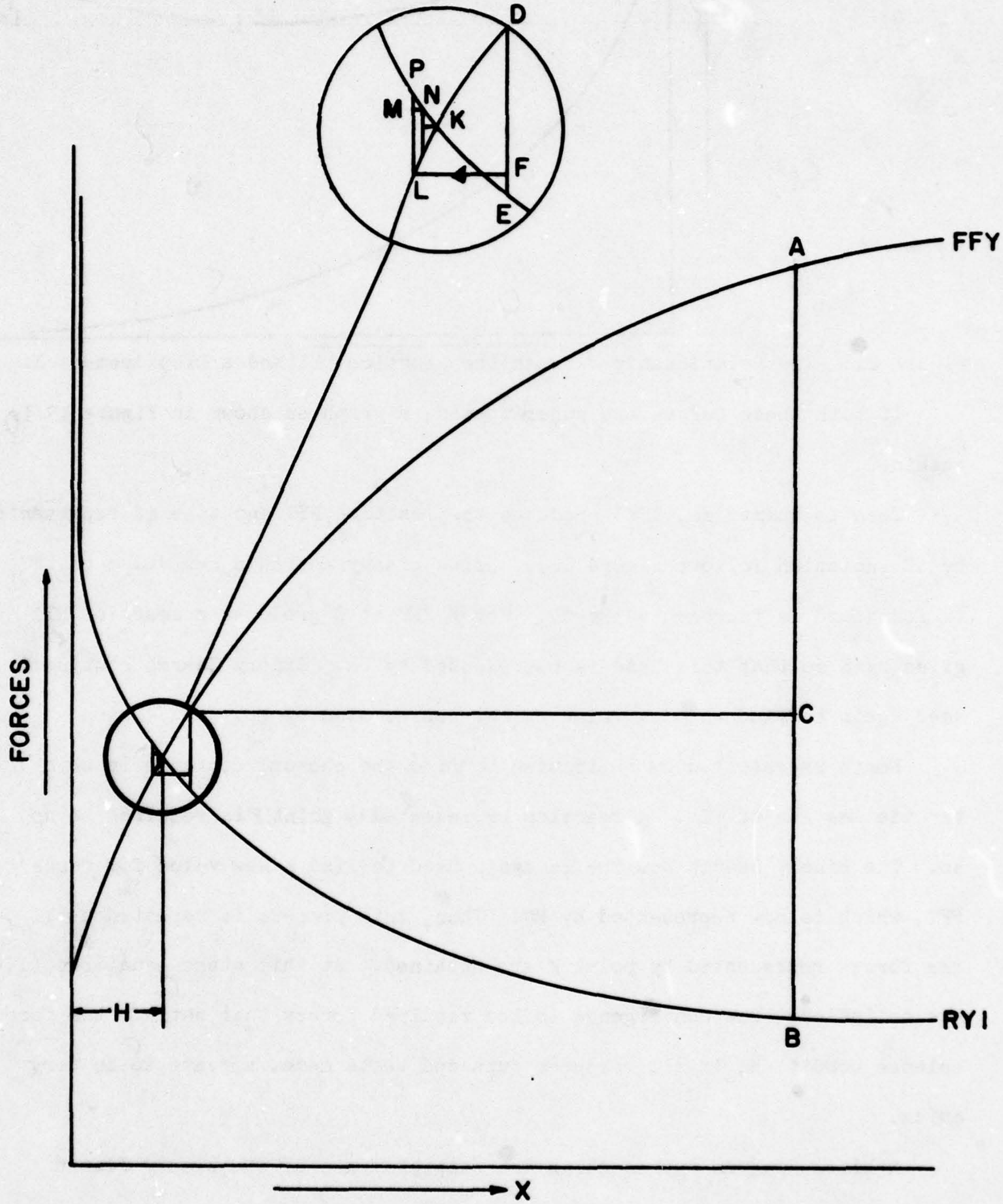


Figure 13: Representation of the Binary Search Routine.

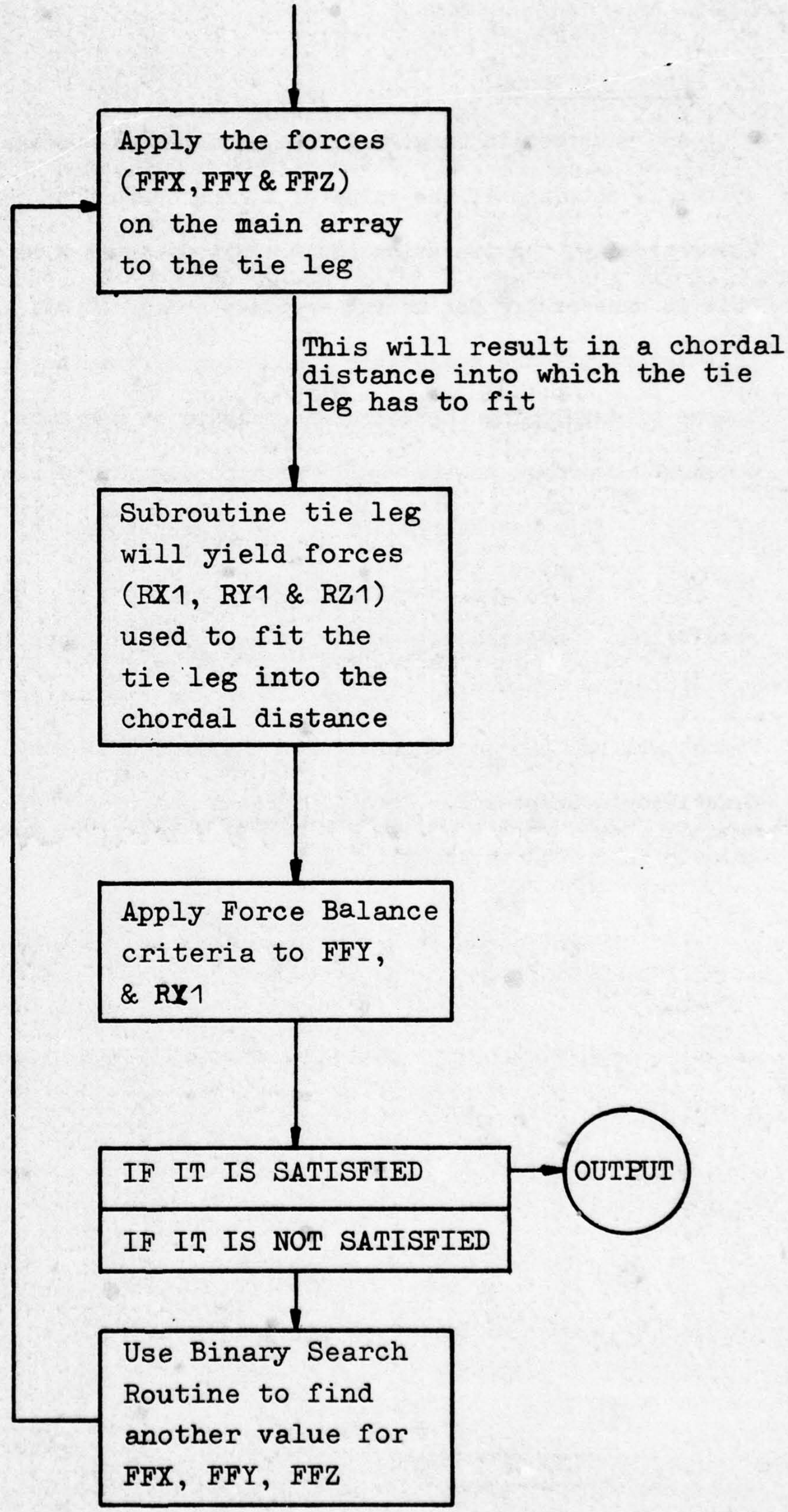


Figure 14: Block Diagram of the Binary Search Routine

B. PRECISION FOCUS

As described in Chapter I, the equilibrium configuration of the array system is obtained if the value of E, the measure of error, is nearly zero. Theoretically, the iteration could continue until E is exactly zero. However, this is unnecessary for useful accuracy and a cut off value COMPE is defined that determines the acceptable completion of the iterative process.* In the course of developing the computer analysis it was found that the tie leg array would not converge to its equilibrium configuration within specified limits of COMPE. This was attributed to the higher levels of required forces in the y-coordinate direction as compared to the other two directions, with the result that δ becomes too small for rapid convergence in all three directions. To overcome this problem, another convergence technique, called Precision Focus, was used in conjunction with the method of convergence that has been described in Chapter I. Precision Focus has been used by Savage[13] and is briefly described in Appendix II.

* A brief discussion of COMPE appears in Appendix II.

CHAPTER V

TESTING THE COMPUTER MODEL

The computer program written to simulate the given array system is listed in Appendix I. This chapter presents a discussion of some testing of this computer model, and some aspects of the general behavior of the array system.

The computer model tested has the following specifications:

The tri-moored structure consisted of three identical legs, each 25,000 ft. long, in the unstressed state. These legs have a diameter of 0.675 inches and a weight in water of 0.606 lb/ft. The extensional rigidity of each cable segment is given as $2.2\text{x}10^6$ lb. The co-efficient of normal drag is assumed as 1.40 for the entire range of current velocities.

The tie leg cable has a diameter of 0.675 inches and an extensional rigidity of $2.2\text{x}10^6$ lb. The length and weight of the cable was determined internally by the program.

As described in Chapter II, the basic approach in the analysis of the given system has been to divide the array system into the following coupled parts:

1. The tri-moored array structure
2. The tie leg array structure

This approach was thought to be most practical because results obtained, namely the displacements of the subsurface buoy in the given system, could be compared readily with the displacements obtained from the analysis of a tri-moored structure without a tie leg for which a computer program has been published.[9] Also, it is possible to study the behavior of the main structure and the tie leg separately. To check the program output the following extreme cases

were analyzed on the computer.

1. When the tie leg is attached near the top of the tri-moored structure, where the tie leg has negligible length
2. When the tie leg is attached near the bottom of the tri-moored structure, where the tie leg is essentially connected between two of three anchor points

Since both of these are limiting conditions where the tensions will be taken up by the anchors in one case and where the tie leg is of negligible length in the other, the system should behave similarly to a simple tri-moored structure as shown in Figure 1. To look at these extreme conditions and at the general case of the tie leg attached anywhere on the main structure, the computer model was used and the results are discussed in the next three sections.

A. TESTING THE COMPUTER MODEL WHEN THE TIE LEG IS NEAR THE TOP OF THE TRI-MOORED STRUCTURE

The computer program is written in such a manner that it is not possible to place the tie leg precisely at the apex. To cope with this problem, it was decided to break the main cable into unequal segments such that the first and last segments were only of 5 feet length. Each of the cables was broken up into 20 segments.

This resulted in a simulation which allowed the tie leg to be put at a distance of five feet from the top. The displacements obtained from this configuration were used for comparison purposes. Many different conditions of tie leg parameters were tried and in each case, the tie leg structural analysis gave similar results to the already tested program for a simple tri-moored structure[9]. For example, with a tie leg of 6.12 feet in length and the weight per foot of cable at 0.505 lb./ft., the displacement of the buoy due to a standard test current, for the case of a tri-moored array without this tie leg is:

Horizontal deflection of the buoy = 36.95 ft.

Vertical deflection of the buoy = -11.50 ft.

The displacement of the buoy due to the same test current with the tie leg cable attached between two cables near the apex of the tri-moored system is:

Horizontal deflection of the buoy = 35.12 ft.

Vertical deflection of the buoy = 11.50 ft.

The results obtained from this test condition compare favorably with the results obtained from the analysis of a simple tri-moored structure.

B. <u>TESTING THE COMPUTER MODEL WHEN THE TIE LEG IS LOCATED NEAR THE BOTTOM OF THE TRI-MOORED STRUCTURE</u>

For this condition, the tie leg was attached near the bottom (five feet up each leg), between two of three anchor points.

The length of the tie leg was 30612.8 feet and weight of the cable per foot was 0.367 lb. This weight of the cable was determined internally by the program so as to make the tie leg array slightly positively buoyant.

The displacements of the buoy when placed in the test current with the tie leg are as follows:

1. Horizontal Deflection of the buoy = 39.61 ft.
2. Vertical Deflection of the buoy = -12.45 ft.

These results should be compared with the displacements of the standard tri-moored buoy, as listed above.

C. <u>PRELIMINARY STUDY USING THE COMPUTER MODEL</u>

Besides the above two test cases, the installed position of a tie leg was varied along the length of the main cables. This was done in order to study the behavior of the model for different positions of a tie leg. While the purpose of this report is not to conduct a complete study of

system behavior, enough data was gathered to predict the general behavior of a tie leg in a tri-moored structure. This behavior is presented in Figure 15 and 16 wherein the vertical horizontal deflections of the buoy are plotted against the position of the tie leg. The curves should be considered only as approximate since the data points were obtained from calculations using slightly different tie leg cable weights for each location. This was done as a matter of convenience. The error introduced does not alter the general behavior or the conclusion that horizontal deflections of the apex are increased by approximately a factor of two and the vertical deflections of the apex are increased by approximately a factor of four. If a prototype system is contemplated, a more detailed analysis should be conducted.

From the graphs it can be inferred that worse deflections, both horizontal and vertical, are encountered, as one would expect, when the tie leg is at a position near the middle. The current used is perpendicular to the tie leg.

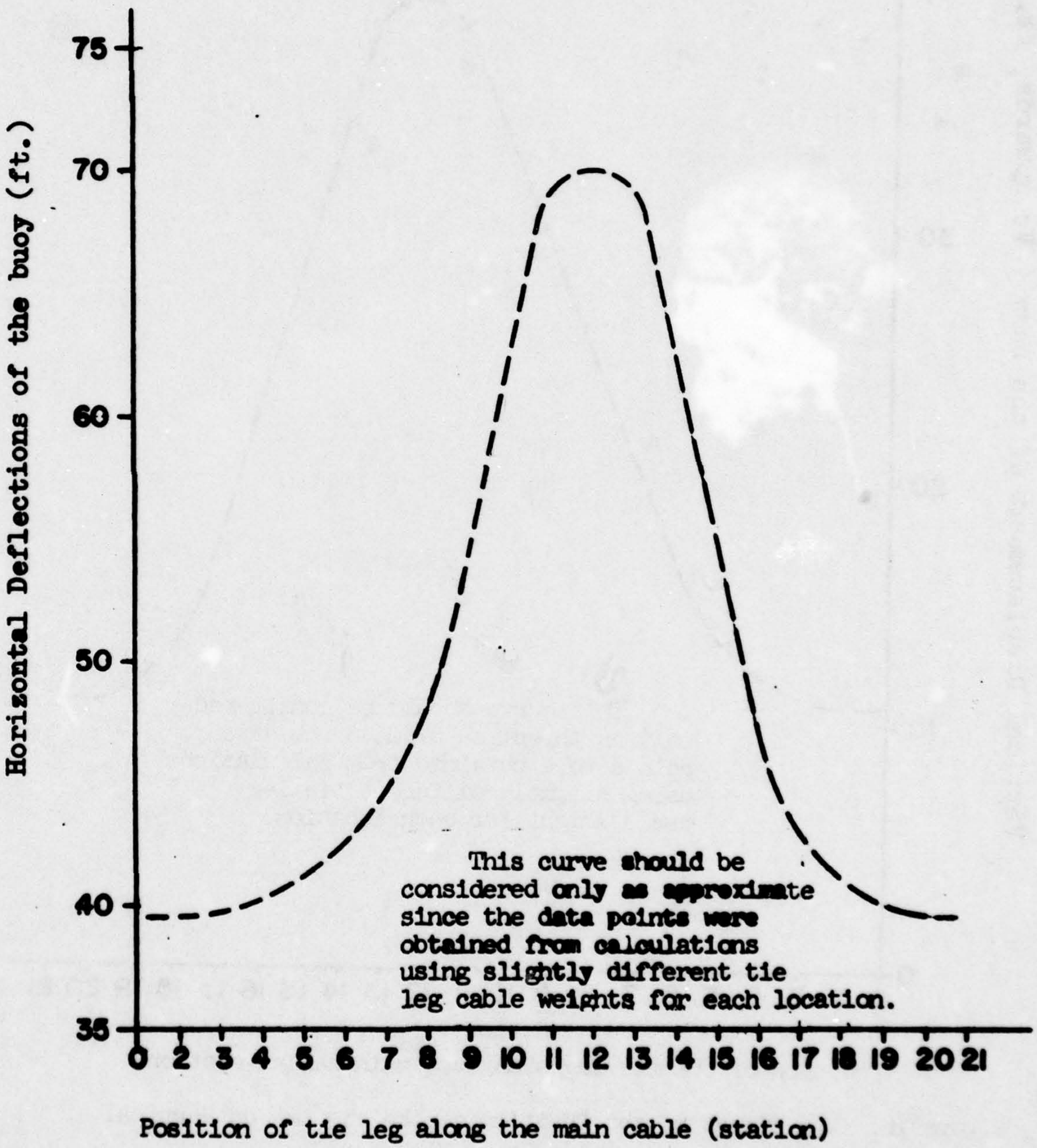


Figure 15: The Effect of the Position of the Tie Leg on Horizontal Deflection of the Buoy

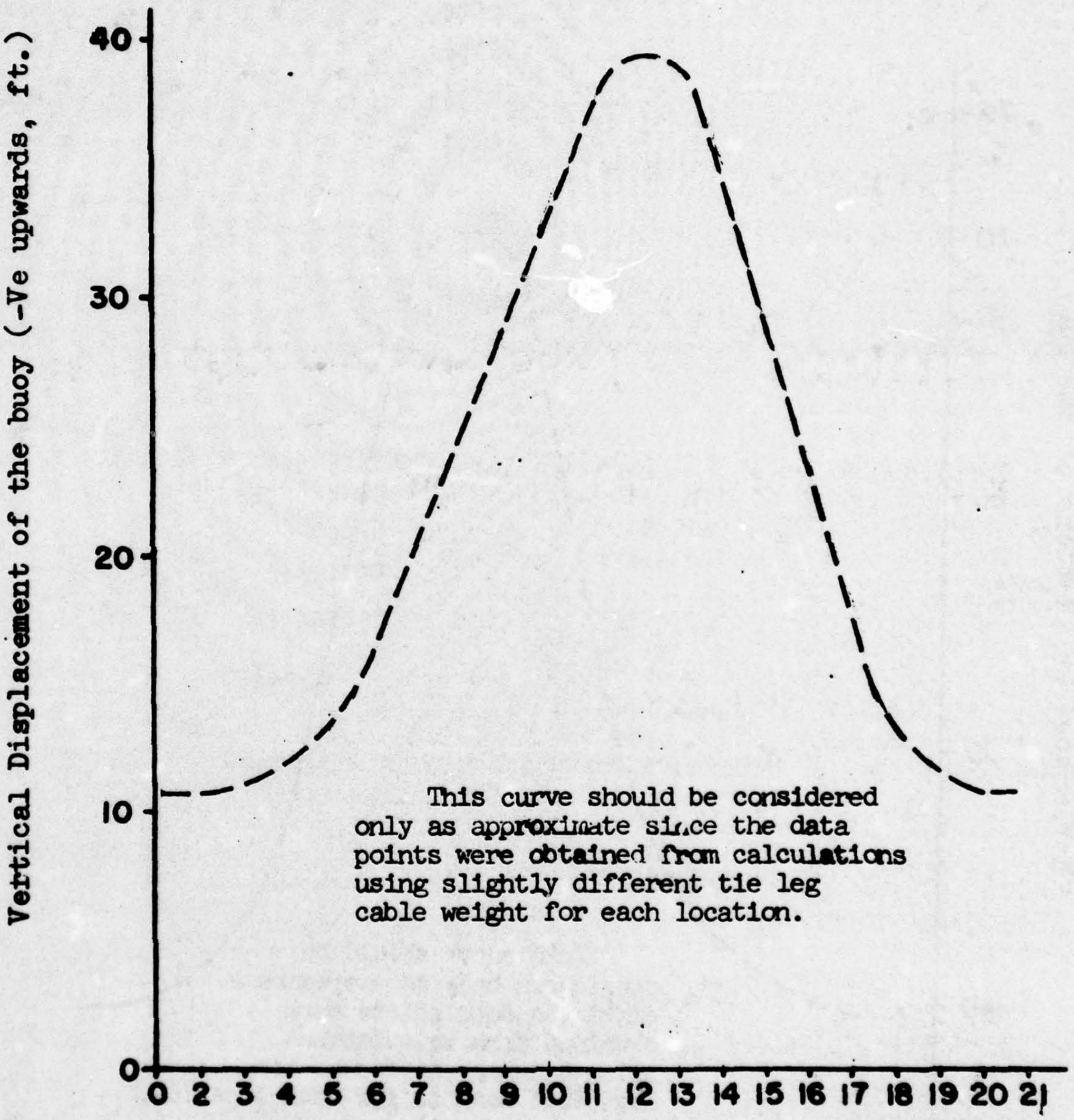


Figure 16: The Effect of the Position of the Tie Leg on Vertical Deflections of the Array

APPENDIX I

THE COMPUTER PROGRAM

A. DESCRIPTION

The computer program, required to simulate a tri-moored buoy with a tie leg is reproduced in this appendix. This program is written in FORTRAN IV and can be compiled and executed on most of IBM-360 facilities. The facility at the University of New Hampshire is IBM 360-40 and the computer program has been specifically adapted to it.

The program consists of 14 subroutines besides the main section. Comment cards at the beginning of each of these sections describe the nomenclature and in some cases the purpose of each subroutine.

The program, as written, is restricted to 20 segments and to 10 elemental devices per segment in each of the main arrays and to 21 segments and 5 elemental devices in each tie leg array. This is only for convenience and these numbers can easily be changed by changing the dimensions of the common arrays in the main program and in the subroutine and functions.

Since the length of the tie leg is dependent upon the pretensioning, the length of each segment is determined internally. The tie leg is made positively buoyant by about 2% and as such, the weight per unit feet is also computed internally.

The total length of the computer program is $(FB58)_{16}$. If at any facility the computer memory is inadequate, then K and M dimensions for all the arrays are reduced to the largest values of KMAS (m,n) and JMAX(m) in the case of the tie leg--depending upon any particular analysis.

B. INPUT DATA CARDS

The complete input data is controlled by subroutine INPUT. Thus, data cards in the program correspond to this subroutine.

This subroutine has been broken up into four parts:

First part consists of reading in of data that is valid for the main arrays and the tie leg arrays.

Second part deals with data relevant only to the main arrays.

Third part consists of reading in of data for the tie leg array.

Finally, the last part deals with the profiles of the hydrodynamic current as it attacks the main array and the tie leg respectively.

1. The first input card contains: COMPE, COMPD, STAPSI, DELPSI, ENDPSI, and TIECOM. F10.3 FORMAT

COMPE	COMPD	STAPSI	DELPSI	ENDPSI	TIE COM
Comparison value for E-Error Function	Comparison value for displacement	First current angle to be analyzed in leg	Change of current angle in degrees	Final current angle in degrees	Comparison value to meet force balance criteria

2. The next three cards contain the Anchor Positions, AA1 = (=X), BB1 (=Y), CC1 (=Z) -F 10.3 FORMAT

AA1(=X)	BB1(=Y)	CC1(Z)	
X of Anchor 1	Y of Anchor 1	Z of Anchor 1	card 2
X of Anchor 2	Y of Anchor 2	Z of Anchor 2	card 3
X of Anchor 3	Z of Anchor 3	Z of Anchor 3	card 4

3. The fifth card contains the number of stations per cable, MMAX(N) - I 5 FORMAT

MMAX(1)	MMAX(2)	MMAX(3)
No. of stations on cable 1	No. of stations on cable 2	No. of stations on cable 3

4. The next group of cards contain the physical properties of the cable segments and the discrete elements. This starts with cable 1, which goes from anchor point to subsurface buoy--followed by cables 2 and 3.

FORMAT OF CARDS DESCRIBING THE PROPERTIES OF THE CABLE SEGMENTS

BLBAR	WC(M,N)	XTEN(M,N)	TDRAG(M,N)
(M,N) F 10.2	F 10.2	F 10.2	F 10.2
Unstressed length (ft.)	Weight/ ft. (lb./ft.)	Extensional regidity (lb.)	Normal drag coefficient

CABDIA (M,N) F 10.2	PDRAG(M,N) F 10.2	KMAX(M,N) I-5
Cable Dia. (Inches)	Parallel Drag Coeff.	No. of Discrete Elements

following each one of these is KMAX(m,n) cards giving the physical properties of the discrete elements

SBAR(k,m,n)	WE (k,m,n)	DRAG CF(k,m,n)	XREA(k,m,n)
Length segment (m-1,n) element	weight lb.	Drag. coeff.	X-sectional area

5. The next group of data cards contain input data for the tie leg array.

   1. First card in this group contains the number of station on the main array to which tie leg is attached, - I 3 FORMAT

L - I 3
No. of stations on the main array to which tie leg is attached

2. The next consists of number of stations into which tie leg is broken - I 2 FORMAT

MMAXN I-2
No. of stations on tie leg

3. The next group consists of data for the physical properties of the tie leg array segments.

XXTEN(M)	TTDRAG(M)	CABDA(M)	PFDRAG(M)	JMAX(M)
Extensional rigidity (lb.)	Normal drag coeff.	Cable diameter (inches)	Parallel drag coeff.	No. of discrete elements

following each one of these is JMAX(M) cards giving the physical properties of the discrete elements

WEE(J,M)	DRAGCF(J,M)	XXREA(J,M)
Weight (lb.)	Drag coeff.	X-sectional area ft.^{2}

Finally the last group of data cards deal with the input values for the current profile.

H(k) F 10.3	V(k) F 10.3
Z coordinate where the velocity profile changes slope (ft.)	The magnitude of current at Z=H(k) (ft./sec.)

```
      COMMON/C19/TIECOM,L
      COMMON/C20/ITEST,JTEST,LTEST,MTEST,LTIE,MCON
C
C     READ AND PRINT INPUT INFORMATION
C
      CALL INPUT
C
C     COMPUTE MIDSEGEMENT DISCRETE ELEMENT KTILDA(M,N)
C
      DO 2 N = 1,3
      MX = MMAX(N)
      DO 2 M = 2,MX
      KX = KMAX(M,N)
      DO 1 K = 1,KX
      IF(SBAR(K,M,N).GT.BLBAR(M,N)/2.)GO TO 2
    1 CONTINUE
      K = KX+1
    2 KTILDA(M,N) = K-1
C
C     SUBSCRIPTS FOR PRIMARY ANCHOR
C
      X(1,1) = AA1(1)
      Y(1,1) = BB1(1)
      Z(1,1) = CC1(1)
C
C     INITIAL VALUES
      LEAP = 1
      JUMP = 1
      PSI = STAPSI
      PI = 3.14159265
      LOOPE = 0
      LOOPA = 0
      ITEST = 0
      JTEST = 0
      MTEST = 0.
C
C     INITALIZE FORCES FOR TIE LEG POSITION
C
      DO 230 N = 1,3
      MX = MMAX(N)
      DO 230 M = 2,MX
      FFX(M,N) = 0.
      FFY(M,N) = 0.
  230 FFZ(M,N) = 0.
      FFX(L,2) = 0.
      FFY(L,2) = 100.
      FFZ(L,2) = 0.
      FFX(L,3) = 0.
      FFY(L,3) = -100.
      FFZ(L,3) = 0.
C
C     COMPUTE STATION GRAVITY FORCES W(M,N) AND INITIAL FORCES FX,FY,FZ
      CALL GFORC
C
C     COMPUTE CABLE FORCES RX,RY,RZ-TENSION T(M,N) AND STRESSED LENGTH(M,N)
C
    3 DO 7 NN = 1,3
      N = 4-NN
      MX = MMAX(N)
```

```
C     THIS PROGRAM BY SUBHASH C PAHUJA
C     THIS PROGRAM PERFORMS THE MOTION ANALYSIS OF A TRI-MOORED BUOY
C     STRUCTURE HAVING AN AUXILIARY CABLE BETWEEN TWO CABLE LEGS
C     SOLUTION IS BY THE METHOD OF IMAGINARY REACTIONS AND SUCCESSIVE
C     APPROXIMATIONS
C     THIS PROGRAM UTLIZES THE CONCEPTS OF THE PROGRAM DATUBA WRITTEN BY
C     SKOP AND KAPLAN OF THE NAVAL RESEARCH LABORATORY
C     NOMENCLATURE FOR THE MAIN STRUCTURE
C     N = CABLE INDEX
C     M = STATION INDEX
C     K = DISCRETE ELEMENT INDEX
C     CABLE SEGMENT(M,N)
C     BLBAR(M,N) = UNSTRESSED LENGTH
C     BL(M,N) = STRESSED LENGTH
C     WC(M,N) = WEIGHT/FOOT
C     XTEN(M,N) = EXTENSIONAL RIGIDITY
C     MU(M,N) = DRAG CHARACRESTIC
C     RD(M,N) = DRAG COEFFICENT RATIO
C     KMAX(M,N) = NO. OF DISCRETE ELEMENTS IN SEGMENT(M,N)
C     KTILDA(M,N) = NO. OF DISCRETE ELEMENTS IN FIRST HALF SEGMENT(M,N)
C     T(M,N) = TENSION IN SEGMENT(M,N)
C     (ALPHA(M,N),BETA(M,N),GAMMA(M,N)) = DIRECTION COSINES
C     DISCRETE ELEMENT(K,M,N)
C     SBAR(K,M,N) = UNSTRESSED LENGTH FROM STATION (M,N) TO ELEMENT(K,M,N)
C     WE(K,M,N) = WEIGHT OF THE ELEMENT
C     MUE(K,M,N) = DRAG CHARATERISTIC
C     STATION (M,N)
C     (X(M,N),Y(M,N),Z(M,N)) = COORDINATES
C     MMAX(N) = NO. OF STATIONS ON CABLE(N)
C     (AA1(N),BB1(N),CC1(N)) = ANCHOR COORDINATES
C     HORIZL(M,N) = HORIZL DISPLACEMENT FROM THE GRAVITY POSITION
C     HEIGHT(M,N) = VERTICAL DISPLACEMENT FROM THE GRAVITY POSITION
C     E = ERROR FUNCTION
C     COMPE = COMPARISION VALUE FOR E
C     TIECOM = COMPARISION VALUE FOR THE FORCE BALANCE CONDITION
C     PSI = ANGLE OF ATTACK OF CURRENT
C     STAPSI = STARTING VALUE OF THE ANGLE OF ATTACK OF CURRENT
C     DELPSI = INCREMENT IN THE VALUE OF THE STAPSI
C     ENDPSI = LAST VALUE OF THE ANGLE OF ATTACK OF CURRENT
      REAL BL,BLBAR,BLT,MU,MUE,MUU,MUUE
      COMMON/C1/XF,X(21,3),YF,Y(21,3),ZF,Z(21,3)
      COMMON/C2/FX(21,3),FY(21,3),FZ(21,3)
      COMMON/C3/W(21,3),WC(21,3),WE(10,21,3)
      COMMON/C4/MMAX(3),KMAX(21,3),KTILDA(21,3)
      COMMON/C5/BLBAR(21,3),BL(21,3),SBAR(10,21,3),T(21,3),BLT(21,3)
      COMMON/C6/AA1(3),BB1(3),CC1(3),E,DELTA,JUMP,LOOPE,LOOPA
      COMMON/C7/HORIZL(21,3),HEIGHT(21,3)
      COMMON/C8/CX(21,3),CY(21,3),CZ(21,3)
      COMMON/C9/AV(5),BV(5),VF,V(5),HF,H(5)
      COMMON/C10/COMPE,COMPD,PSI,STAPSI,DELPSI,ENDPSI
      COMMON/C11/XTEN(21,3),MU(21,3),MUE(10,21,3),RD(21,3)
      COMMON/C12/ALPHA(21,3),BETA(21,3),GAMMA(21,3)
      COMMON/C13/RX(21,3),RY(21,3),RZ(21,3)
      COMMON/C14/XO(21,3),YO(21,3),ZO(21,3)
      COMMON/C15/XB(21,3),YB(21,3),ZB(21,3)
      COMMON/C16/FXP(3),FYP(3),FZP(3),XP(3),YP(3),ZP(3)
      COMMON/C17/DELTA1,PDELTA
      COMMON/C18/FFX(21,3),FFY(21,3),FFZ(21,3)
```

```
      GO TO(5,4,4),N
    4 RX(MX,N) = FX(MX,N)
      RY(MX,N) = FY(MX,N)
      RZ(MX,N) = FZ(MX,N)
      GO TO 6
    5 RX(MX,1) = FX(MX,1)+RX(2,2)+RX(2,3)
      RY(MX,1) = FY(MX,1)+RY(2,2)+RY(2,3)
      RZ(MX,1) = FZ(MX,1)+RZ(2,2)+RZ(2,3)
    6 T(MX,N) = SQRT(RX(MX,N)**2+RY(MX,N)**2+RZ(MX,N)**2)
      BL(MX,N) = BLBAR(MX,N)*(1.+T(MX,N)/XTEN(MX,N))
      BLT(MX,N) = BL(MX,N)/T(MX,N)
      MX = MX-1
      DO 7 MM = 2,MX
      M = MX-MM+2
      IF(N.EQ.1)GO TO 8
      IF(M.EQ.L)GO TO 220
    8 RX(M,N) = FX(M,N)+RX(M+1,N)
      RY(M,N) = FY(M,N) + RY(M+1,N)
      RZ(M,N) = FZ(M,N) + RZ(M+1,N)
      GO TO 16
  220 RX(M,N) = FX(M,N) + RX(M+1,N) + FFX(L,N)
      RY(M,N) = FY(M,N)+RY(M+1,N)+FFY(L,N)
      RZ(M,N) = FZ(M,N)+RZ(M+1,N)+FFZ(L,N)
   16 T(M,N) = SQRT(RX(M,N)**2+RY(M,N)**2+RZ(M,N)**2)
      BL(M,N) = BLBAR(M,N)*(1.+T(M,N)/XTEN(M,N))
    7 BLT(M,N) = BL(M,N)/T(M,N)
C
C     COMPUTE X,Y,Z COORDINATES OF EACH STATION
C
      DO 10 N = 1,3
      MX = MMAX(N)
      DO 9 M = 2,MX
      X(M,N) = BLT(M,N)*RX(M,N)+X(M-1,N)
      Y(M,N) = BLT(M,N)*RY(M,N)+Y(M-1,N)
    9 Z(M,N) = BLT(M,N)*RZ(M,N)+Z(M-1,N)
      GO TO(27,10),N
   27 DO 110 NN = 2,3
      X(1,NN) = X(MX,1)
      Y(1,NN) = Y(MX,1)
  110 Z(1,NN) = Z(MX,1)
   10 CONTINUE
C
C     COMPUTE ERROR FUNCTION
C
      LOOPE = LOOPE+1
      E = 0
      DO 11 N = 2,3
      M = MMAX(N)
   11 E = E+((AA1(N)-X(M,N))**2+(BB1(N)-Y(M,N))**2+(CC1(N)-Z(M,N))**2)
      IF(E.GT.COMPE)GO TO(19,50,15),LEAP
C
C     UPDATED DIRECTION COSINES
C
      DO 300 N = 1,3
      MX = MMAX(N)
      DO 300 M = 2,MX
      ALPHA(M,N) = (X(M,N)-X(M-1,N))/BL(M,N)
      BETA(M,N) = (Y(M,N)-Y(M-1,N))/BL(M,N)
  300 GAMMA(M,N) = (Z(M,N)-Z(M-1,N))/BL(M,N)
```

```
C     ERROR FUNCTION COMPARISION SATISFIED
      GO TO(51,52),JUMP
C     PRINT AND STORE EQUILIBRIUM POSITION
   51 CALL TIELEG(X(L,2),Y(L,2),Z(L,2),X(L,3),Y(L,3),Z(L,3))
      MTEST = MTEST + 1
      PDELTA = DELTA
      DELTA = DELTA1
      LEAP = 1
      IF(JTEST.NE.1)GO TO 3
      CALL STAPOS
      JUMP = 2
      LOOPE = 0
      DO 53 N = 1,3
      MX = MMAX(N)
      DO 53 M = 2,MX
      XO(M,N) = X(M,N)
      YO(M,N) = Y(M,N)
      ZO(M,N) = Z(M,N)
      XB(M,N) = X(M,N)
      YB(M,N) = Y(M,N)
      ZB(M,N) = Z(M,N)
   53 CONTINUE
      GO TO 61
C
C     COMPARE ACCURACY OF COORDINATES
C
   52 DO 55 N = 1,3
      MX = MVALUE(N)
      DO 55 M = 2,MX
      IF(ABS(X(M,N)-XO(M,N)).GT.COMPD.OR.
     1ABS(Y(M,N)-YO(M,N)).GT.COMPD.OR.
     2ABS(Z(M,N)-ZO(M,N)).GT.COMPD)GO TO 57
   55 CONTINUE
C
C     ACCURACY SATISFIED-PRINT EQQUILIBRIUM POSITION
C
      ITEST = ITEST+1
      CALL TIELEG(X(L,2),Y(L,2),Z(L,2),X(L,3),Y(L,3),Z(L,3))
      IF(LTEST.NE.200)GO TO 197
C
C
      DO 56 N = 1,3
      MX = MMAX(N)
      DO 56 M = 2,MX
      HORIZL(M,N) = SQRT((X(M,N)-XB(M,N))**2 + (Y(M,N)-YB(M,N))**2)
      HEIGHT(M,N) = Z(M,N)-ZB(M,N)
   56 CONTINUE
      CALL DYNPOS
C
      LOOPE = 0
      LOOPA = 0
      LTEST = 100
      GO TO 60
C     ACCURACY NOT ADEQUATE-REITERATE
C
   57 DO 59 N = 1,3
      MX = MVALUE(N)
      DO 59 M = 2,MX
      XO(M,N) = X(M,N)
```

```
      YO(M,N) = Y(M,N)
      ZO(M,N) = Z(M,N)
   59 CONTINUE
      GO TO 61
C
C     ERROR FUNCTION COMPARISION NOT SATISFIED
C
   50 IF(E.LT.EP)GO TO 20
C     INCREASE IN ERROR FUNCTION
      DELTA = DELTA/2.
C
C     COMPUTE ERROR FUNCTION
C
   12 DE = DELTA/SQRT(EP)
      DO 13 N = 2,3
      MX = MMAX(N)
      FX(MX,N) = FXP(N)+(AA1(N)-XP(N))*DE
      FY(MX,N) = FYP(N)+(BB1(N)-YP(N))*DE
      FZ(MX,N) = FZP(N)+(CC1(N)-ZP(N))*DE
   13 CONTINUE
C
C     CHECK CHANGES IN IMAGINARY REACTIONS
C
      DO 14 N = 2,3
      MX = MMAX(N)
      IF(FX(MX,N).NE.FXP(N).OR.
     1FY(MX,N).NE.FYP(N).OR.
     2FZ(MX,N).NE.FZP(N))GO TO 3
   14 CONTINUE
      LEAP = 3
      GO TO 3
C     NO CHANGE TIME TO QUIT
   15 CALL EXITT
      GO TO 100
C     DECREASE IN ERROR FUNCTUON
   19 LEAP = 2
   20 EP = E
      DO 21 N = 2,3
      MX = MMAX(N)
      XP(N) = X(MX,N)
      YP(N) = Y(MX,N)
      ZP(N) = Z(MX,N)
      FXP(N) = FX(MX,N)
      FYP(N) = FY(MX,N)
      FZP(N) = FZ(MX,N)
   21 CONTINUE
      GO TO 12
C
C     INCREASE CURRENT ANGLE
C
   60 PSI = PSI+DELPSI
      IF(PSI.GE.ENDPSI)GO TO 100
   61 COSPSI = COS(PSI*PI/180.)
      SINPSI = SIN(PSI*PI/180.)
      GO TO 62
  197 JUMP = 2
      LOOPE = 0
      LOOPA = 0
      GO TO 61
```

```
   62 DELTA = DELTA1
      LEAP = 1
      LOOPA = LOOPA+1
C
C DRAG COEFFICIENTS
C
      DO 30  N = 1, 3
      MX = MMAX(N)
      DO 30  M = 2, MX
      CADELT=SQRT((BETA(M,N)*COSPSI-ALPHA(M,N)*SINPSI)**2
     1                    + GAMMA(M,N)**2 )
      BUFFER = ALPHA(M,N)*COSPSI + BETA(M,N)*SINPSI
      CX(M,N)=MU(M,N)*(CADELT*
     1           ( (GAMMA(M,N)**2 + BETA(M,N)**2)*COSPSI
     2           - ALPHA(M,N) * BETA(M,N) * SINPSI )
     3           + RD(M,N) * ALPHA(M,N) * BUFFER )
      CY(M,N)=MU(M,N)*(CADELT*
     1           ( (GAMMA(M,N)**2 + ALPHA(M,N)**2)*SINPSI
     2           - ALPHA(M,N) * BETA(M,N) * COSPSI )
     3           + RD(M,N) * BETA(M,N) * BUFFER )
   30 CZ(M,N)=MU(M,N)*GAMMA(M,N)*BUFFER*(RD(M,N)-CADELT)
C
C COMPUTE CABLE DRAG FORCES HX,HY,HZ-AND ELEMENT DRAG FORCES HXE,HYE
C
      DO 40  N = 1, 3
      MX = MVALUE(N)
      DO 40  M = 2, MX
      MXMN=MX-M+N
      IF(MXMN-2)23,24,24
   24 A1 = AREA(M,N,1)
      A2 = AREA(M+1,N,2)
      HX = CX(M,N) * A1 + CX(M+1,N) * A2
      HY = CY(M,N) * A1 + CY(M+1,N) * A2
      HZ = CZ(M,N) * A1 + CZ(M+1,N) * A2
      DT = AREA(M,N,3)+AREA(M+1,N,4)
      HXE = DT * COSPSI
      HYE = DT * SINPSI
      GO TO 26
   23 A1 = AREA(MX,1,1)
      A2 = AREA(2,2,2)
      A3 = AREA(2,3,2)
      HX = CX(M,N) * A1 + CX(2,2) * A2 + CX(2,3) * A3
      HY = CY(M,N) * A1 + CY(2,2) * A2 + CY(2,3) * A3
      HZ = CZ(M,N) * A1 + CZ(2,2) * A2 + CZ(2,3) * A3
      DT = AREA(MX,1,3)+AREA(2,2,4)+AREA(2,3,4)
      HXE = DT * COSPSI
      HYE = DT * SINPSI
C     NEW TOTAL FORCES
   26 FX(M,N) = HX + HXE
      FY(M,N) = HY + HYE
      FZ(M,N) = HZ + W(M,N)
   40 CONTINUE
      GO TO 3
  100 STOP
      END
```

```
      SUBROUTINE TIELEG(X1,Y1,Z1,X2,Y2,Z2)
C     SUBROUTINE TIELEG IS USED TO SATISFY THE FOLLOWING CONSTRAINTS
C     THE GEOMATRICAL COMPATIBILITY
C     THE FORCE BALANCE
C     COORDINATES X1,Y1,Z1,X2,Y2,Z2 ARE TRANSFERRED FROM MAIN TO MEET
C     THE FIRST CONDITION
C     THE SECOND CONDITION IS SATISFIED USING THE SEARCH ROUTINE
C     NOMENCLATURE FOT THE TIELEG ARRAY
C     M = STATION INDEX
C     CABLE SEGMENT(M)
C     BAR(M) = UNSTRESSED LENGTH
C     B(M) = STRESSED LENGTH
C     WWC(M) = WEIGHT/FOOT
C     XXTEN(M) = EXTENSIONAL RIGIDITY
C     MUU(M) = DRAG CHARACRESTIC
C     RRD(M) = DRAG COEFFICENT RATIO
C     JMAX(M) = NO. OF DISCRETE ELEMENTS IN SEGMENT(M)
C     JTILDA(M) = NO. OF DISCRETE ELEMENTS IN FIRST HALF SEGMENT(M)
C     ST(M) = TENSION IN SEGMENT(M)
C     (ALPHA(M),BETA(M),GAMMA(M)) = DIRECTION COSINES
C     DISCRETE ELEMENT(J,M)
C     SAR(J,M) = UNSTRESSED LENGTH FROM STATION(M) TO ELEMENT(J,M)
C     WEE(J,M) = WEIGHT OF THE ELEMENT
C     MUUE(J,M) = DRAG CHARATERISTIC
C     STATION (M)
C     (X(M),Y(M),Z(M)) = COORDINATES
C     MMAXN = NO. OF STATIONS ON THE TIELEG ARRAY
C     NX(1),Y(1),Z(1)) = END COORDINATES FOR THE TIELEG ARRAY
C     (X(MX),Y(MX),Z(MX)) = END COORDINATES FOR THE TIELEG ARRAY
C     HORIZL(M) = HORIZL DISPLACEMENT FROM THE GRAVITY POSITION
C     HEIGHT(M) = VERTICAL DISPLACEMENT FROM THE GRAVITY POSITION
      REAL BL,BLBAR,BLT,MU,MUE,MUU,MUUE
      DIMENSION XO(22),YO(22),ZO(22),XB(22),YB(22),ZB(22),
     1XP(1),YP(1),ZP(1),FXP(1),FYP(1),FZP(1),AA(22),BB(22),CC(22),
     2W(22),PREM(22),DISCRT(22)
      COMMON/H1/FX(22),FY(22),FZ(22),RX(22),RY(22),RZ(22)
      COMMON/H2/RX1(22),RY1(22),RZ1(22)
      COMMON/H3/BAR(22),B(22),BT(22),ST(22),XXTEN(22)
      COMMON/H4/JMAX(22),JTILDA(22),SAR(5,22)
      COMMON/H5/MUU(22),MUUE(5,22),WEE(5,22),WWC(22),RRD(22)
      COMMON/H6/ALPHA(22),BETA(22),GAMMA(22)
      COMMON/H7/CX(22),CY(22),CZ(22)
      COMMON/H8/HORIZL(22),HEIGHT(22)
      COMMON/H9/X(22),Y(22),Z(22)
      COMMON/H10/E,DELTA,LOOPE,LOOPA
      COMMON/H11/MMAXN
      COMMON/H12/JUMP,PDIST,DIST
      COMMON/C18/FFX(21,3),FFY(21,3),FFZ(21,3)
      COMMON/C19/TIECOM,L
      COMMON/C9/AV(5),BV(5),VF,V(5),HF,H(5)
      COMMON/C10/COMPE,COMPD,PSI,STAPSI,DELPSI,ENDPSI
      COMMON/C20/ITEST,JTEST,LTEST,MTEST,LTIE,MCON
      DATA PI/3.1415926/
      X(1) = X1
      Y(1) = Y1
      Z(1) = Z1
      MX = MMAXN
      AA(MX) = X2
```

```
      BB(MX) = Y2
      CC(MX) = Z2
      DIST = SQRT((AA(MX)-X(1))**2+(BB(MX)-Y(1))**2+(CC(MX)-Z(1))**2)
      IF(ITEST.GE.1)GO TO 61
      IF(MTEST.GE.1)GO TO 195
      DOMPE = COMPE/2.
      PDIST = DIST
C
C     COMPUTE LENGTH OF SEGEMENT
C
      MX = MMAXN
      TMAXN = MX-1
      DO 200 M = 2,MX
      BAR(M) = DIST/TMAXN
  200 CONTINUE
C
C     COMPUTE WEIGHT/FOOT FOR EACH SEGMENT
C
      DO 116 M = 2,MX
      PREM(M) = 0.
      JX = JMAX(M)
      IF(JX.EQ.0)GO TO 117
      DO 115 J = 1,JX
      PREM(M) = PREM(M) + WEE(J,M)
  115 CONTINUE
      WWC(M) = PREM(M)/BAR(M)
      WWC(M) = -0.99 * WWC(M)
      GO TO 116
  117 WWC(M) = -0.500
  116 CONTINUE
C
C     COMPUTE DISTANCE OF A DISCRETE ELEMENT FROM THE STATION
C
      DO 71 M = 2,MX
      JX = JMAX(M)
      IF(JX.EQ.0)GO TO 71
      SUME = 0.0
      DISCRT(M) = BAR(M)/(JX+1)
      DO 71 K = 1,JX
      SUME = SUME + DISCRT(M)
      SAR(K,M) = SUME
   71 CONTINUE
C
C     COMPUTE MIDSEGEMENT DISCRETE ELEMENT JTILDA(M)
C
      MX = MMAXN
      DO 10 M = 2,MX
      KX = JMAX(M)
      DO 11 K =1,KX
      IF(SAR(K,M).GT.BAR(M)/2.)GO TO 10
   11 CONTINUE
      K = KX+1
   10 JTILDA(M) = K-1
C
C     COMPUTE STATION GRAVITY FORCES W(M) AND INITIAL FORCES FX,FY,FZ
C
      MX = MMAXN
      DO 106 M = 1,MX
      FX(M) = 0.
```

```
  106 FY(M) = 0.
      FZ(1) = 0.
      WT = 0.
      MX = MMAXN-1
      DO 6 M = 2,MX
      WX = 0.
      KB = JTILDA(M)+1
      KX = JMAX(M)
      IF(KB.GT.KX)GO TO 77
      DO 13 K = KB,KX
   13 WX = WX+WEE(K,M)
   77 JX = JTILDA(M+1)
      IF(JX.EQ.0)GO TO 78
      DO 2 K =1,JX
    2 WX = WX+WEE(K,M)
   78 W(M) = WX + (WWC(M)*BAR(M)/2.) + (WWC(M+1)*BAR(M+1)/2.)
      FZ(M) = W(M)
    6 WT = WT + W(M)
      MX = MMAXN
      FZ(MX) = (-1.1) * WT
C
C     INITIALIZATION
C
      SQ2 = SQRT(2.)
      DELTA1 = ABS(SQ2*WT)
      LCON = 0
      LTIE = 0
      MCON = 1
  195 DELTA = DELTA1
      JUMP = 1
      LEAP = 1
      LOOPA = 0
      LOOPE = 0
C
C     COMPUTE CABLE FORCES RX,RY,RZ - TENSION T(M,N) AND STRESSED LENGTH
C
    3 MX = MMAXN
      RX(MX) = FX(MX)
      RY(MX) = FY(MX)
      RZ(MX) = FZ(MX)
      ST(MX) = SQRT(RX(MX)**2+RY(MX)**2+RZ(MX)**2)
      B(MX) = BAR(MX)*(1.+ST(MX)/XXTEN(MX))
      BT(MX) = B(MX)/ST(MX)
      MX = MMAXN-1
      DO 7 MM = 1,MX
      M = MX-MM+1
      GO TO(9,5),M
    5 RX(M) = FX(M)+RX(M+1)
      RY(M) = FY(M) + RY(M+1)
      RZ(M) = FZ(M)+RZ(M+1)
      ST(M) = SQRT(RX(M)**2+RY(M)**2+RZ(M)**2)
      B(M) = BAR(M)*(1.+ST(M)/XXTEN(M))
      BT(M) = B(M)/ST(M)
    9 RX(M) = FX(M)+RX(M+1)
      RY(M) = FY(M)+RY(M+1)
      RZ(M) = FZ(M)+RZ(M+1)
    7 CONTINUE
C
C     COMPUTE X,Y,Z COORDINATES OF EACH STATION
```

```
C
      MX = MMAXN
      DO 8 M = 2,MX
      X(M) = BT(M)*RX(M)+X(M-1)
      Y(M) = BT(M)*RY(M)+Y(M-1)
    8 Z(M) = BT(M)*RZ(M)+Z(M-1)
C
C     COMPUTE ERROR FUNCTION
C
      LOOPE = LOOPE + 1
      E = 0
      M = MMAXN
      E = E+((AA(M)-X(M))**2+(BB(M)-Y(M))**2+(CC(M)-Z(M))**2)
      MX = MMAXN
      IF(E.GT.COMPE)GO TO(19,50,15),LEAP
C
C     UPDATED DIRECTION COSINES
C
      MX = MMAXN
      DO 300 M = 2,MX
      ALPHA(M) = (X(M)-X(M-1))/B(M)
      BETA(M) = (Y(M)-Y(M-1))/B(M)
      GAMMA(M) = (Z(M)-Z(M-1))/B(M)
  300 CONTINUE
C
C     ERROR FUNCTION COMPARISION SATISFIED
C
      GO TO (51,52), JUMP
   51 MX = MMAXN
      DO 235 M = 1,MX
      RX1(M) = RX(M)
      RY1(M) = RY(M)
      RZ1(M) = RZ(M)
  235 CONTINUE
      RX1(1) = -RX1(1)
      RY1(1) = -RY1(1)
      RZ1(1) = -RZ1(1)
C
C     CHECK FOR FORCE BALANCE UNDER GRAVITY FORCES-USE BINARY SEARCH ROUTINE
C
      CALL SEARCH
C     FORCE BALANCE NOT OBTAINED-START AGAIN
      IF(LTEST.NE.100)GO TO 100
C     FORCE BALANCE OBTAINED-PRINT AND STORE EQUILIBRIUM POSITION
C
      JTEST = JTEST + 1
      LTIE = LTIE + 1
      CALL STATS
      MX = MMAXN
      DO 53 M = 2,MX
      XO(M) = X(M)
      YO(M) = Y(M)
      ZO(M) = Z(M)
      XB(M) =X(M)
      YB(M) = Y(M)
      ZB(M) = Z(M)
   53 CONTINUE
      JUMP = 2
      LOOPE = 0
```

```
      GO TO 100
C
C     COMPARE ACCURACY OF COORDINATES
C
   52 MX = MMAXN-1
      DO 55 M = 2,MX
      IF(ABS(X(M)-XO(M)).GT.COMPD.OR.
     1ABS(Y(M)-YO(M)).GT.COMPD.OR.
     2ABS(Z(M)-ZO(M)).GT.COMPD)GO TO 57
   55 CONTINUE
C
C     ACCURACY SATISFIED- PRINT EQUILIBRIUM POSITION FOR HYDRODYNAMIC FORCES
C
      MX = MMAXN
      DO 38 M = 1,MX
      RX1(M) = RX(M)
      RY1(M) = RY(M)
      RZ1(M) = RZ(M)
   38 CONTINUE
      RX1(1) = -RX1(1)
      RY1(1) = -RY1(1)
      RZ1(1) = -RZ1(1)
C
C     CHECK FOR FORCE BALANCE UNDER ACTING FORCES-USE BINARY SEARCH ROUTINE
C
      CALL SEARCH
C     FORCE BALANCE NOT OBTAINED-START AGAIN
      IF(LTEST.NE.200)GO TO 100
C     FORCE BALANCE OBTAIN-PRINT EQUILIBRIUM POSITION FOR
C     HYDERODYNAMIC FORCES
      MX = MMAXN
      DO 56 M = 2,MX
      HORIZL(M) = SQRT((X(M)-XB(M))**2 + (Y(M)-YB(M))**2)
      HEIGHT(M) = Z(M)-ZB(M)
   56 CONTINUE
      CALL DYNAMS
      GO TO 100
C      ACCURACY NOT ADEQUATE - REITRATE
   57 MX = MMAXN-1
      DO 37 M = 2,MX
      XO(M) = X(M)
      YO(M) = Y(M)
      ZO(M) = Z(M)
   37 CONTINUE
      GO TO 62
C
C     TEST IF PRECISION FOCUS SHOULD BE APPLIED
C
   50 IF(ABS(AA(MX)-X(MX)).GE.DOMPE.OR.ABS(CC(MX)-Z(MX)).GE.
     1DOMPE)GO TO 734
      IF(YP(1).EQ.Y(MX))GO TO 734
      DELFYP = (FY(MX)-FYP(1))/(Y(MX)-YP(1))*(BB(MX)-Y(MX))
      FYP(1) = FY(MX)
      YP(1) = Y(MX)
      FY(MX) = FY(MX)+DELFYP
      GO TO 3
C
C     ERROR FUNCTION COMPARISION NOT SATISFIED
C
```

```
  734 IF(E.LT.EP)GO TO 20
C     INCREASE IN ERROR FUNCTION
      DELTA = DELTA/2.
C     COMPUTE IMAGINARY REACTIONS
   12 DE = DELTA/SQRT(EP)
      MX = MMAXN
      FX(MX) = FXP(1)+(AA(MX)-XP(1))*DE
      FY(MX) = FYP(1)+(BB(MX)-YP(1))*DE
      FZ(MX) = FZP(1)+(CC(MX)-ZP(1))*DE
C     CHECK CHANGES IN IMAGINARY REACTIONS
      IF(FX(MX).NE.FXP(1).OR.FY(MX).NE.FYP(1).OR.
     1FZ(MX).NE.FZP(1))GO TO 3
C     NO CHANGE IN FORCE TIME TO QUIT
      LEAP = 3
      GO TO 3
   15 IF(MTEST.GE.1)GO TO 150
      FFY(L,2) = 2.0 * FFY(L,2)
      FFY(L,3) = 2.0 * FFY(L,3)
      GO TO 100
  150 MCON = 2
  162 CALL SEARCH
      GO TO 100
C     DECREASE IN ERROR FUNCTION
   19 LEAP = 2
   20 EP = E
      MX = MMAXN
      XP(1) = X(MX)
      YP(1) = Y(MX)
      ZP(1) = Z(MX)
      FXP(1) = FX(MX)
      FYP(1) = FY(MX)
      FZP(1) = FZ(MX)
      GO TO 12
C     ADD HYDRODYNAMIC FORCE TO THE SYSTEM
   61 COSPSI = COS(PSI*PI/180.)
      SINPSI = SIN(PSI*PI/180.)
   62 DELTA = DELTA1
      LEAP = 1
      LOOPA = LOOPA + 1
C     DRAG COOFICENTS
      MX = MMAXN
      DO 31 M = 2,MX
      CAPDEL = SQRT((BETA(M)*COSPSI-ALPHA(M)*SINPSI)**2+GAMMA(M)**2)
      BUFFER = ALPHA(M)*COSPSI + BETA(M)*SINPSI
      CX(M) = MUU(M)*(CAPDEL*(GAMMA(M)**2+BETA(M)**2)*COSPSI-
     1ALPHA(M)*BETA(M)*SINPSI+RRD(M)*BETA(M)*BUFFER)
      CY(M) = MUU(M)*(CAPDEL*(GAMMA(M)**2+ALPHA(M)**2)*SINPSI-
     1ALPHA(M)*BETA(M)*COSPSI+RRD(M)*BETA(M)*BUFFER)
      CZ(M) = MUU(M)*GAMMA(M)*BUFFER*(RRD(M)-CAPDEL)
   31 CONTINUE
      MX = MMAXN-1
      DO 41 M = 2,MX
      A1 = TAREA(M,1)
      A2 = TAREA(M+1,2)
      HX = CX(M)*A1+CX(M+1)*A2
      HY = CY(M)*A1+CY(M+1)*A2
      HZ = CZ(M)*A1+CZ(M+1)*A2
      DT = TAREA(M,3) + TAREA(M+1,4)
      HXE = DT*COSPSI
```

```
      SUBROUTINE INPUT
      REAL BL,BLBAR,BLT,MU,MUE,MUU,MUUE
      COMMON/C3/W(21,3),WC(21,3),WE(10,21,3)
      COMMON/C4/MMAX(3),KMAX(21,3),KTILDA(21,3)
      COMMON/C5/BLBAR(21,3),BL(21,3),SBAR(10,21,3),T(21,3),BLT(21,3)
      COMMON/C6/AA1(3),BB1(3),CC1(3),E,DELTA,JUMP,LOOPE,LOOPA
      COMMON/C9/AV(5),BV(5),VF,V(5),HF,H(5)
      COMMON/C10/COMPE,COMPD,PSI,STAPSI,DELPSI,ENDPSI
      COMMON/C11/XTEN(21,3),MU(21,3),MUE(10,21,3),RD(21,3)
      COMMON/H3/BAR(22),B(22),BT(22),ST(22),XXTEN(22)
      COMMON/H4/JMAX(22),JTILDA(22),SAR(5,22)
      COMMON/H5/MUU(22),MUUE(5,22),WEE(5,22),WWC(22),RRD(22)
      COMMON/H11/MMAXN
      COMMON/C19/TIECOM,L
C
C COMPARISON VALUES AND CURRENT ANGLE REQUIREMENTS
      WRITE(6,101)
  101 FORMAT('1',15X,'INPUT DATA COMMON TO,BOTH,THE TIE LEG AND THE
     1TRI MOORED STRUCTURE'/)
      WRITE(6,35)
   35 FORMAT(5X,'COMPARISION VALUES AND CURRENT ANGLE REQUIREMENTS'/)
      READ(5,1)COMPE,COMPD,STAPSI,DELPSI,ENDPSI,TIECOM
    1 FORMAT(F10.2,5F10.0)
      WRITE(6,30)COMPE,COMPD,STAPSI,DELPSI,ENDPSI,TIECOM
   30 FORMAT(15X,'COMPARISION VALUE FOR E = ',E15.6/15X,'COMPARISION VAL
     1UE FOR DISPLACEMENT =',E15.6/15X,'INITIAL CURRENT ANGLE =',F8.3,
     2'DEGREES'/15X,'INCREMENT OF ANGLE =',F8.3,'DEGREES'/15X,'FINAL CUR
     3RENT ANGLE =',F8.3,'DEGREES'/15X'COMPARISION VALUE FOR THE TIE LEG
     4JOINT = ',E16.5/)
C
      WRITE(6,102)
  102 FORMAT(///15X,' INPUT DATA FOR THE TRI MOORED STRUCTURE'//)
C
C ANCHOR POSITIONS
      WRITE(6,40)
   40 FORMAT(10X,'ANCHOR POSITIONS'/)
      DO 31 N = 1,3
   31 READ(5,2)AA1(N),BB1(N),CC1(N)
    2 FORMAT(3F10.0)
C NO. OF STATIONS PER CABLE
      WRITE(6,45)(AA1(N),BB1(N),CC1(N),N=1,3)
   45 FORMAT(2X,'AA1=',F10.0,'BB1=',F10.0,'CC1=',F10.0/)
      WRITE(6,50)
   50 FORMAT(10X,'NO. OF STATIONS PER CABLE'/)
      READ(5,3)(MMAX(N),N=1,3)
    3 FORMAT(3I5)
      WRITE(6,55)(N,MMAX(N),N=1,3)
   55 FORMAT(2X,'CABLE NO.',I1,I5)
      READ(5,36)L
   36 FORMAT(I2)
      WRITE(6,60)
   60 FORMAT(/,5X,'PROPERTIES OF SEGMENTS AND DISCRETE ELEMENTS'/)
      DO 10 N=1,3
      WRITE(6,70)N
   70 FORMAT(60X,'CABLE NO.',I1/)
      WRITE(6,65)
   65 FORMAT(4X,'M',3X,'STRESSED LEN.',3X,'WEIGHT/FT',3X,'EXT.RIGIDIT
     1Y',2X,'DRAG CHRACTER',1X,'DRAG COE. RATIO',2X,'K',
```

```
      HYE = DT*SINPSI
   26 FX(M) = HX + HXE
      FY(M) = HY + HYE
      FZ(M) = HZ + W(M)
   41 CONTINUE
      GO TO 3
  100 RETURN
      END
```

```
     2 6X,'SBAR',9X,'WEIGHT',11X,'MUE')
      MMN=MMAX(N)
      DO 10 M=2,MMN
      READ(5,15)BLBAR(M,N),WC(M,N),TDRAG,CABDIA,PDRAG,XTEN(M,N),
     1KMAX(M,N)
   15 FORMAT(5F10.3,F10.2,I2)
      MU(M,N)=1.94*TDRAG*CABDIA/24.
      RD(M,N)=PDRAG/TDRAG
      I=M-1
      WRITE(6,24)I,BLBAR(M,N),WC(M,N),XTEN(M,N),MU(M,N),RD(M,N),
     1KMAX(M,N)
   24 FORMAT(I5,5E15.6,I5)
      IF(KMAX(M,N).EQ.0) GO TO 10
      KKN=KMAX(M,N)
      DO 5 K=1,KKN
      READ(5,20)SBAR(K,M,N),WE(K,M,N),DRAGCF,XAREA
   20 FORMAT(4F10.2)
      MUE(K,M,N)=1.94*DRAGCF*XAREA/2.
    5 WRITE(6,25)SBAR(K,M,N),WE(K,M,N),MUE(K,M,N)
   25 FORMAT(85X,3E15.6)
   10 CONTINUE
C
C     INPUT DATA FOR TIELEG
C
      WRITE(6,103)
  103 FORMAT('1',15X,'INPUT DATA FOR TIE LEG'//)
      WRITE(6,37)L
   37 FORMAT(10X,'TIE LEG JOINS CABLE AT STATION NO.',I2/)
      READ(5,74)MMAXN
   74 FORMAT(I3)
      WRITE(6,72)MMAXN
   72 FORMAT(5X,'NO. OF STATIONS ON THE TIELEG=',I3)
      WRITE(6,104)
  104 FORMAT(4X,'M',3X,'EXT.RIGIDITY',3X,'DRAG CHRACTER',2X,'DRAG COE.
     1ATIO',3X,'J',20X,'WEIGHT',10X,'MUUE'//)
      MX = MMAXN
      DO 17 M = 2,MX
      READ(5,14)XXTEN(M),TTDRAG,CABDA,PPDRAG,JMAX(M)
   14 FORMAT(4F10.3,I2)
      MUU(M) = 1.94*TTDRAG*CABDA/24.
      RRD(M) = PPDRAG/TTDRAG
      I = M-1
      WRITE(6,16)I,XXTEN(M),MUU(M),RRD(M),JMAX(M)
   16 FORMAT(I4,3E16.7,I4)
      IF(JMAX(M).EQ.0)GO TO 17
      LKN = JMAX(M)
      DO 18 K = 1,LKN
      READ(5,29)WEE(K,M),GRAGCF,XXAREA
   29 FORMAT(3F10.2)
      MUUE(K,M) = 1.94*GRAGCF*XXAREA/2.
   18 WRITE(6,21)WEE(K,M),MUUE(K,M)
   21 FORMAT(75X,2E15.6)
   17 CONTINUE
C     PROVIDE VELOCITY PROFILE IN SUBROUTINE VPROFILE
      CALL VPROFL
      WRITE(6,75)
   75 FORMAT(40X,'XXXXXXXXXXXXXXXXXXXXXXX',T1,'1'///)
      RETURN
      END
```

```
      SUBROUTINE SEARCH
C
C     THIS SUBROUTINE INVOLVES THE CONCEPTS OF BINARY SEARCH
C     A NEW VALUE OF THE FORCES IS FOUND THAT ALWAYS LIES INBETWEEN
C     THE TWO PREVIOUS VALUES
C     THE CONCEPT IS SIMILIAR TO THE DAMPING FORCE AND AS SUCH BRINGS ABOUT
C     FAST CONVERGENCE
C
      DIMENSION ZXP(2),ZYP(2),ZZP(2)
      COMMON/C4/MMAX(3),KMAX(21,3),KTILDA(21,3)
      COMMON/C18/FFX(21,3),FFY(21,3),FFZ(21,3)
      COMMON/C19/TIECOM,L
      COMMON/H11/MMAXN
      COMMON/H2/RX1(22),RY1(22),RZ1(22)
      COMMON/C20/ITEST,JTEST,LTEST,MTEST,LTIE,MCON
      GO TO(55,156),MCON
   55 ZXP(1) = FFX(L,2)
      ZYP(1) = FFY(L,2)
      ZZP(1) = FFZ(L,2)
      ZXP(2) = FFX(L,3)
      ZYP(2) = FFY(L,3)
      ZZP(2) = FFZ(L,3)
C     TEST FOR FORCE BALANCE
      MX = MMAXN
      IF((FFX(L,2)+RX1(1)).GT.TIECOM.OR.
     1   (FFY(L,2)+RY1(1)).GT.TIECOM.OR.
     2   (FFZ(L,2)+RZ1(1)).GT.TIECOM)GO TO 77
   76 IF((FFX(L,3)+RX1(MX)).GT.TIECOM.OR.
     1   (FFY(L,3)+RY1(MX)).GT.TIECOM.OR.
     2   (FFZ(L,3)+RZ1(MX)).GT.TIECOM)GO TO 77
      IF(LTIE.GE.1)GO TO 90
C     FORCE BALANCE UNDER GRAVITY FORCES OBTAINED-RETURN AND PRINT RESULTS
      LTEST = 100
      GO TO 100
C     FORCE BALANCE UNDER ACTING FORCES OBTAINED-RETURN AND PRINT RESULTS
   90 LTEST = 200
      GO TO 100
  156 MX = MMAXN
      RY1(1) = FFY(L,2)
      RY1(MX) = FFY(L,3)
C     FORCE BALANCE NOT OBTAINED-USE BINARY SEARCH TO OBTAIN NEW VALUES
C     AND START ALL OVER AGAIN
   77 FFX(L,2) = -RX1(1)
      XNO = ABS(RY1(1))
      YNO = ABS(ZYP(1))
      HNO = AMIN1(XNO,YNO)
      ZNO = ABS(XNO-YNO)
      FFY(L,2) = (ZNO/2. + HNO)
      FFZ(L,2) = -RZ1(1)
      FFX(L,3) = -RX1(MX)
      X1NO = ABS(RY1(MX))
      Y1NO = ABS(ZYP(2))
      H1NO = AMIN1(X1NO,Y1NO)
      Z1NO = ABS(X1NO-Y1NO)
      FFY(L,3) = -(Z1NO/2. + H1NO)
      FFZ(L,3) = -RZ1(MX)
  100 RETURN
      END
```

```
      SUBROUTINE GFORC
      REAL BL,BLBAR,BLT,MU,MUE,MUU,MUUE
      COMMON/C2/FX(21,3),FY(21,3),FZ(21,3)
      COMMON/C3/W(21,3),WC(21,3),WE(10,21,3)
      COMMON/C4/MMAX(3),KMAX(21,3),KTILDA(21,3)
      COMMON/C5/BLBAR(21,3),BL(21,3),SBAR(10,21,3),T(21,3),BLT(21,3)
      COMMON/C6/AA1(3),BB1(3),CC1(3),E,DELTA,JUMP,LOOPE,LOOPA
      COMMON/C17/DELTA1,PDELTA
C     COMPUTE STATION GRAVITY FORCES W(M,N)- AND INITIAL FORCES FX,FY,FZ
      WT = 0.
      DO 3  N = 1, 3
      MX = MMAX(N) - 1
      DO 3  M = 2, MX
      WX = 0.
      FX(M,N) = 0.
      FY(M,N) = 0.
      KB = KTILDA(M,N) + 1
      KX = KMAX(M,N)
      IF(KB.GT.KX) GO TO 10
      DO 1  K = KB, KX
    1 WX = WX + WE(K,M,N)
   10 KX = KTILDA(M+1,N)
      IF(KX.EQ.0) GO TO 30
      DO 2  K = 1, KX
    2 WX = WX + WE(K,M+1,N)
   30 W(M,N) = WX+WC(M,N)*BLBAR(M,N)/2.+WC(M+1,N)*BLBAR(M+1,N)/2.
      FZ(M,N) = W(M,N)
    3 WT = WT + W(M,N)
      WX = 0.
      FX(MMAX(1),1) = 0.
      FY(MMAX(1),1) = 0.
      KB = KTILDA(MMAX(1),1) + 1
      KX = KMAX(MMAX(1),1)
      IF(KB.GT.KX) GO TO 20
      DO 4  K = KB, KX
    4 WX = WX + WE(K,MMAX(1),1)
   20 CONTINUE
      DO 6  N = 2, 3
      KX = KTILDA(2,N)
      FX(MMAX(N),N) = 0.
      FY(MMAX(N),N) = 0.
      IF(KX.EQ.0) GO TO 6
      DO 5  K = 1, KX
    5 WX = WX + WE(K,2,N)
    6 WX = WX+WC(2,N)*BLBAR(2,N)/2.
      W(MMAX(1),1) = WX+WC(MMAX(1),1)*BLBAR(MMAX(1),1)/2.
      FZ(MMAX(1),1) = W(MMAX(1),1)
      DO 35 N = 2,3
      FX(1,N) = FX(MMAX(1),1)
      FY(1,N) = FY(MMAX(1),1)
   35 FZ(1,N) = FZ(MMAX(1),1)
      WT = WT + W(MMAX(1),1)
      DO 7  N = 2, 3
    7 FZ(MMAX(N),N) = -WT / 3.
C
C     COMPUTE INITIAL DELTA
      SQ2 = SQRT ( 2. )
      DELTA1 = ABS(SQ2*WT/3.)
```

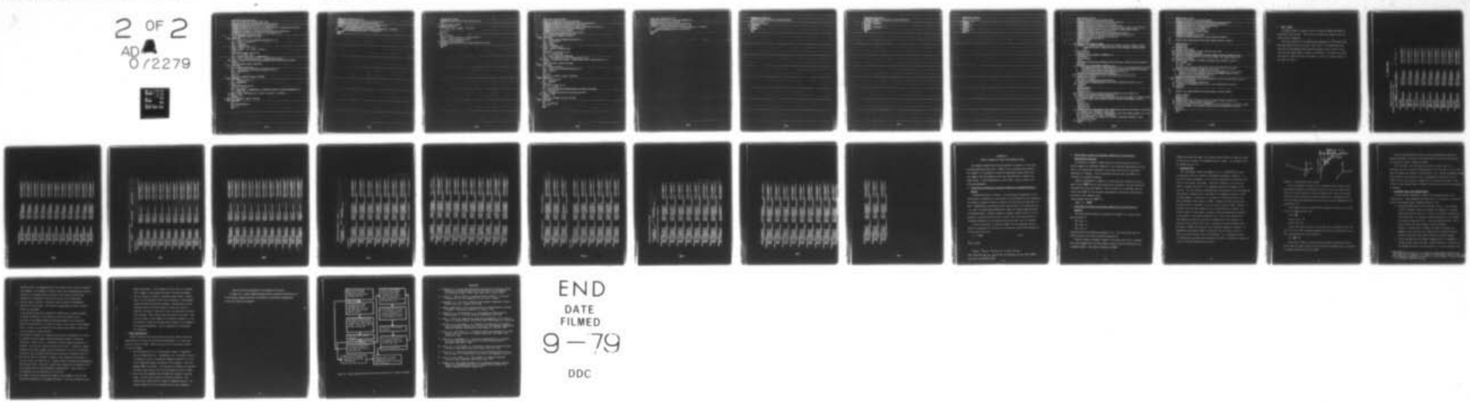
```
      DELTA = DELTA1
      RETURN
      END
```

AD-A072 279 NEW HAMPSHIRE UNIV DURHAM ENGINEERING DESIGN AND ANA--ETC F/G 13/10
A COMPUTER ANALYSIS OF A TRI-MOORED BUOY STRUCTURE WITH AN INTE--ETC(U)
MAY 72 S C PAHUJA, R W CORELL

UNCLASSIFIED TR-110 NL

2 OF 2

AD A072279



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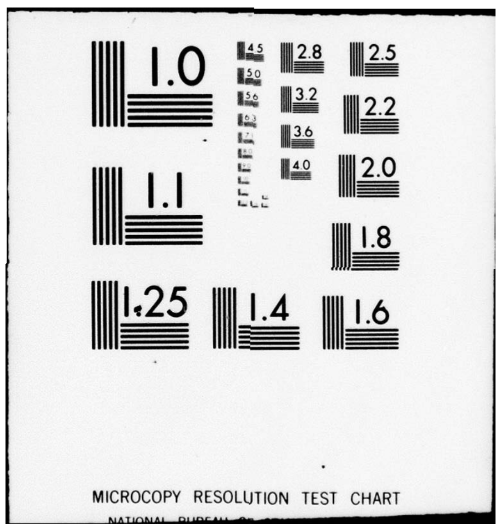
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1.1
1.25
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1.6
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4.0
4.5
5.0
5.6
6.3
MICROCOPY RESOLUTION TEST CHART

```
      FUNCTION AREA(M,N,IGO)
      REAL BL,BLBAR,BLT,MU,MUE,MUU,MUUE
      COMMON/C1/XF,X(21,3),YF,Y(21,3),ZF,Z(21,3)
      COMMON/C4/MMAX(3),KMAX(21,3),KTILDA(21,3)
      COMMON/C5/BLBAR(21,3),BL(21,3),SBAR(10,21,3),T(21,3),BLT(21,3)
      COMMON/C9/AV(5),BV(5),VF,V(5),HF,H(5)
      COMMON/C11/XTEN(21,3),MU(21,3),MUE(10,21,3),RD(21,3)
      COMMON/C12/ALPHA(21,3),BETA(21,3),GAMMA(21,3)
      GO TO(100,200,300,400),IGO
C     LINE INTEGRAL BELOW STATION
  100 CONTINUE
      KL = LIMIT(Z(M-1,N)+GAMMA(M,N)*BL(M,N)/2.)
      KU = LIMIT ( Z(M,N) )
      TOP = BL(M,N)
      BOT = BL(M,N)/2.
    2 KMIN = MINO ( KU, KL )
      KTOP = KMIN - 1 + IABS ( KU-KL )
      SUM = 0.
      IF(KMIN.GT.KTOP) GO TO 10
      DO 1  K = KMIN, KTOP
      XI = (H(K)-Z(M-1,N)) / GAMMA(M,N)
    1 SUM = SUM + AREAS(M,N,K,XI) - AREAS(M,N,K+1,XI)
   10 AREA = SYGN(KU-KL)*SUM+AREAS(M,N,KU,TOP)-AREAS(M,N,KL,BOT)
      RETURN
C     LINE INTEGRAL ABOVE STATION
  200 CONTINUE
      KL = LIMIT(Z(M-1,N))
      KU = LIMIT(Z(M-1,N)+GAMMA(M,N)*BL(M,N)/2.)
      TOP = BL(M,N)/2.
      BOT = 0.
      GO TO 2
C     DRAG OF ELEMENTS BELOW STATION
  300 CONTINUE
      KB = KTILDA(M,N) + 1
      KX = KMAX(M,N)
    5 SUM = 0.
      IF(KB.GT.KX)GO TO 40
      DO 4 K = KB, KX
      ZT = Z(M-1,N) + GAMMA(M,N) * SBAR(K,M,N)*(1.+T(M,N)/XTEN(M,N))
      J = LIMIT( ZT )
    4 SUM = SUM + MUE(K,M,N) * (AV(J) + BV(J) * ZT)**2
   40 AREA = SUM
      RETURN
C DRAG OF ELEMENTS ABOVE STATION
  400 CONTINUE
      KB = 1
      KX = KTILDA(M,N)
      GO TO 5
      END
```

```
      FUNCTION AREAS(M,N,K,XI)
      COMMON/C1/XF,X(21,3),YF,Y(21,3),ZF,Z(21,3)
      COMMON/C9/AV(5),BV(5),VF,V(5),HF,H(5)
      COMMON/C12/ALPHA(21,3),BETA(21,3),GAMMA(21,3)
      AREAS = (AV(K)+BV(K)*Z(M-1,N))**2 * XI
     1      +(AV(K)+BV(K)*Z(M-1,N))*BV(K)*GAMMA(M,N) * (XI**2)
     2      +(BV(K)*GAMMA(M,N))**2 * (XI**3/3.)
      RETURN
      END
```

```
      SUBROUTINE VPROFL
      COMMON/C9/AV(5),BV(5),VF,V(5),HF,H(5)
      K=1
    1 READ(5,2)H(K),V(K)
    2 FORMAT(2F10.0)
      IF ( H(K) .GE. 40000. ) GO TO 3
      K = K + 1
      GO TO 1
    3 KX = K
      DO 4 K=2,KX
      BV(K) = (V(K)-V(K-1)) / (H(K)-H(K-1))
      AV(K) = V(K-1)-BV(K)*H(K-1)
    4 WRITE(6,9)AV(K),BV(K)
    9 FORMAT(10X,6HAV(K)=,E16.5/10X,6HBV(K)=,E16.5)
      RETURN
      END
```

```
      FUNCTION TAREA(M,MGO)
      REAL BL,BLBAR,BLT,MU,MUE,MUU,MUUE
      COMMON/H3/BAR(22),B(22),BT(22),ST(22),XXTEN(22)
      COMMON/H4/JMAX(22),JTILDA(22),SAR(5,22)
      COMMON/H5/MUU(22),MUUE(5,22),WEE(5,22),WWG(22),RRD(22)
      COMMON/H6/ALPHA(22),BETA(22),GAMMA(22)
      COMMON/H9/X(22),Y(22),Z(22)
      COMMON/C9/AV(5),BV(5),VF,V(5),HF,H(5)
      GO TO(1000,2000,3000,4000),MGO
C     LINE INTEGRAL ABOVE STATION
 1000 CONTINUE
      KL = LIMIT(Z(M-1)+GAMMA(M)*B(M)/2.)
      KU = LIMIT(Z(M))
      TOP = B(M)
      BOT = B(M)/2.
    2 KMIN = MINO(KU,KL)
      KTOP = KMIN-1+IABS(KU-KL)
      SUM = 0.
      IF(KMIN.GT.KTOP)GO TO 10
      DO 1 K = KMIN,KTOP
      XI = (H(K)-Z(M-1))/GAMMA(M)
    1 SUM = SUM+TAREAS(M,K,XI)-TAREAS(M,K+1,XI)
   10 TAREA = SYGN(KU-KL)*SUM + TAREAS(M,KU,TOP)-TAREAS(M,KL,BOT)
      RETURN
C     LINE INTEGRAL BELOW STATION
 2000 CONTINUE
      KL = LIMIT(Z(M-1))
      KU = LIMIT(Z(M-1)+GAMMA(M)*B(M)/2.)
      TOP = B(M)/2.
      BOT = 0.
      GO TO 2
C     DRAG OF ELEMENTS ABOVE STATIONS
 3000 CONTINUE
      KB = JTILDA(M)+1
      KX = JMAX(M)
    5 SUM = 0.
      IF(KB.GT.KX)GO TO 20
      DO 4 K = KB,KX
      ZT = Z(M-1)+GAMMA(M)*SAR(K,M)*(1.+ST(M)/XXTEN(M))
      J = LIMIT(ZT)
    4 SUM = SUM+MUUE(K,M)*(AV(J)+BV(J)*ZT)**2
   20 TAREA = SUM
      RETURN
C     DRAG OF ELEMENTS BELOW STATION
 4000 CONTINUE
      KB = 1
      KX = JTILDA(M)
      GO TO 5
      END
```

```
      FUNCTION TAREAS(M,K,XI)
      COMMON/H6/ALPHA(22),BETA(22),GAMMA(22)
      COMMON/H9/X(22),Y(22),Z(22)
      COMMON/C9/AV(5),BV(5),VF,V(5),HF,H(5)
      TAREAS = (AV(K)+BV(K)*Z(M-1))**2 * XI
     1      +(AV(K)+BV(K)*Z(M-1))*BV(K)*GAMMA(M) * (XI**2)
     3     +(BV(K)*GAMMA(M))**2 * (XI**3/3.)
      RETURN
      END
```

```
      FUNCTION LIMIT(ZT)
      COMMON/C9/AV(5),BV(5),VF,V(5),HF,H(5)
      DO 1 J = 2,5
      IF(ZT-H(J))2,2,1
    1 CONTINUE
    2 LIMIT = J
      RETURN
      END
```

```
      FUNCTION MVALUE(N)
      COMMON/C4/MMAX(3),KMAX(21,3),KTILDA(21,3)
      GO TO(1,2,2),N
    1 MVALUE = MMAX(N)
      RETURN
    2 MVALUE = MMAX(N) - 1
      RETURN
      END
```

```
      FUNCTION SYGN(J)
      IF ( J ) 1, 2, 3
    1 SYGN = -1.
      RETURN
    2 SYGN = 0
      RETURN
    3 SYGN = 1.
      RETURN
      END
```

```
      SUBROUTINE OUTPUT
      REAL BL,BLBAR,BLT,MU,MUE,MUU,MUUE
      COMMON/C1/XF,X(21,3),YF,Y(21,3),ZF,Z(21,3)
      COMMON/C2/FX(21,3),FY(21,3),FZ(21,3)
      COMMON/C4/MMAX(3),KMAX(21,3),KTILDA(21,3)
      COMMON/C5/BLBAR(21,3),BL(21,3),SBAR(10,21,3),T(21,3),BLT(21,3)
      COMMON/C6/AA1(3),BB1(3),CC1(3),E,DELTA,JUMP,LOOPE,LOOPA
      COMMON/C7/HORIZL(21,3),HEIGHT(21,3)
      COMMON/C10/COMPE,COMPU,PSI,STAPSI,DELPSI,ENDPSI
      COMMON/C11/XTEN(21,3),MU(21,3),MUE(10,21,3),RD(21,3)
      COMMON/C13/RX(21,3),RY(21,3),RZ(21,3)
      COMMON/C17/DELTA1,PDELTA
      ENTRY STAPOS
      WRITE(6,13)
   16 WRITE(6,5)E,PDELTA,LOOPE
    5 FORMAT( 1X,41HEQUILIBRIUM POSITION UNDER GRAVITY FORCES,//10X,
     1    2HE=,E16.9,10X, 6HDELTA=,E16.9,10X,19HNO.OF ERROR LOOPS=
     2    ,I5)
    6 DO 10 N=1,3
      WRITE(6,7)N
    7 FORMAT(//,3X,13HCABLE NUMBER=,I2)
      MX=MMAX(N)
      DO 10 M=2,MX
      I=M-1
      WRITE(6,8)I,FX(M,N),FY(M,N),FZ(M,N),X(M,N),Y(M,N),Z(M,N),T(M,N),
     1BL(M,N)
    8 FORMAT(/,5X,15HSEGMENT NUMBER=,I2,/
     1   10X,8HFX(M,N)=,E16.9,10X,8HFY(M,N)=,E16.9,10X,8HFZ(M,N)=,E16.9/
     2    10X,7HX(M,N)=,E16.9,10X,7HY(M,N)=,E16.9,10X,7HZ(M,N)=,E16.9/
     3    10X,8H T(M,N)=,E16.9,10X,8HBL(M,N)=,E16.9)
      WRITE(6,639)RX(M,N),RY(M,N),RZ(M,N)
  639 FORMAT(10X,8HRX(M,N)=,E16.9,10X,8HRY(M,N)=,E16.9,10X,
     18HRZ(M,N)=,E16.9)
      GO TO(10,9),JUMP
    9 WRITE(6,11)HORIZL(M,N),HEIGHT(M,N)
   11 FORMAT(15X,12HHORIZL(M,N)=,E16.9,10X,12HHEIGHT(M,N)=,E16.9)
   10 CONTINUE
      RETURN
      ENTRY DYNPOS
      WRITE(6,13)
      WRITE(6,116)
  116 FORMAT(13X,'EQUILIBRIUM POSITION UNDER ACTING FORCES'//)
   17 WRITE(6,12)E,DELTA,LOOPE,LOOPA,PSI
   12 FORMAT(10X,2HE=,E16.9,10X,6HDELTA=,E16.9/13X,19HNO. OF ERROR LOOPS
     1=,I5,10X,22HNO. OF ACCURACY LOOPS=,I5/15X,14HCURRENT ANGLE=,
     2F8.3/)
      GO TO 6
      ENTRY EXITT
      WRITE(6,13)
      WRITE(6,14)
   14 FORMAT(1X//1X,90HPROBLEM NOT COMPLETED, DELTA HAS GOTTEN TOO SMALL
     1TO CHANGE THE IMAGINARY REACTIONS
     2/1X,100HEITHER ACCURACY REQUIREMENTS ARE TOO SMALL(COMPE) OR A CAB
     3LE HAS GONE SLACK (CHECK TENSIONS).
     4/1X,55HPRINTOUT IS GIVEN FOR TROUBLE SHOOTING PURPOSES ONLY.      )
      GO TO(16,17),JUMP
   13 FORMAT ( 1H1 )
      END
```

```
      SUBROUTINE TIEOUT
      REAL BL,BLBAR,BLT,MU,MUE,MUU,MUUE
      COMMON/H1/FX(22),FY(22),FZ(22),RX(22),RY(22),RZ(22)
      COMMON/H3/BAR(22),B(22),BT(22),ST(22),XXTEN(22)
      COMMON/H4/JMAX(22),JTILDA(22),SAR(5,22)
      COMMON/H8/HORIZL(22),HEIGHT(22)
      COMMON/H9/X(22),Y(22),Z(22)
      COMMON/H10/E,DELTA,LOOPE,LOOPA
      COMMON/H11/MMAXN
      COMMON/H12/JUMP,PDIST,DIST
      COMMON/G10/COMPE,COMPD,PSI,STAPSI,DELPSI,ENDPSI
C
C     OUTPUT FOR EQUILIBRIUM POSITION UNDER GRAVITY FORCES
C
      ENTRY STATS
      WRITE(6,13)
   13 FORMAT(1H1)
      WRITE(6,100)PDIST
  100 FORMAT(10X,'LENGTH OF THE TIELEG=',E16.9/)
   26 WRITE(6,25)E,DELTA,LOOPE
   25 FORMAT(1X41HEQUILIBRIUM POSITION UNDER GRAVITY FORCES.//10X,
     12HE=,F16.9,10X,6HDELTA=,E16.9,10X,19HNO. OF ERROR LOOPS=,I5)
   27 WRITE(6,101)DIST
  101 FORMAT(10X,'CHORDAL DISTANCE BETWEEN END POINTS=',E16.9/)
      MX = MMAXN
      DO 20 M = 2,MX
      I = M-1
      WRITE(6,28)I,FX(M),FY(M),FZ(M),X(M),Y(M),Z(M),ST(M),B(M)
   28 FORMAT(/,5X,'SEGMENT NUMBER =',I2,/10X,
     1   6HFX(M)=,E16.9,10X,6HFY(M)=,E16.9,10X,6HFZ(M)=,E16.9,/10X,
     2   5HX(M)=,E16.9,10X,5HY(M)=,E16.9,10X,5HZ(M)=,E16.9,/10X,
     3  6HST(M)=,E16.9,10X,5HB(M)=,E16.9)
      WRITE(6,1000)RX(M),RY(M),RZ(M)
 1000 FORMAT(10X,6HRX(M)=,E16.9,10X,6HRY(M)=,E16.9,10X,6HRZ(M)=,E16.9)
      GO TO (20,29),JUMP
   29 WRITE(6,11)HORIZL(M),HEIGHT(M)
   11  FORMAT(15X,10HHORIZL(M)=,E16.9,10X,10HHEIGHT(M)=,E16.9)
   20 CONTINUE
      RETURN
C
C     OUTPUT FOR EQUILIBRIUM POSITION UNDER ACTING FORCES
C
      ENTRY DYNAMS
      WRITE(6,13)
      WRITE(6,16)
   16 FORMAT(10X,'EQUILIBRIUM POSITION UNDER ACTING FORCES'//)
   17 WRITE(6,12)E,DELTA,LOOPE,LOOPA,PSI
   12 FORMAT(10X,2HE=,E16.9,10X,6HDELTA=,E16.9/13X,19HNO. OF ERRCR LOOPS
     1=,I5,10X,22HNO. OF ACCURACY LOOPS=,I5/15X,14HCURRENT ANGLE=,
     2F8.3/)
      GO TO 27
      END
```

D. SAMPLE OUTPUT

A computer OUTPUT as obtained from the subroutine OUTPUT and TIEOUT is reproduced in this section. This is done to present the format in which the output should be expected.

First part consists of the equilibrium configuration of the array system when only gravity forces are acting. Next follows the configuration under the action of hydrodynamic forces produced because of the current (in this case only zero degree angle of attack is considered). The printout for main cable array is shown only for cable number 1. There is a similar format for the other two cables.

D. Sample Output

```
      LENGTH OF THE TIELEG= 0.306128047E 05

EQUILIBRIUM POSITION UNDER GRAVITY FORCES

      E=      0.026809946          DELTA= 0.477388382E 01              NO. OF ERROR LOOPS=   29
      CHORDAL DISTANCE BETWEEN END POINTS= 0.306128047E 05

   SEGEMENT NUMBER= 1
      FX(M)= 0.0                     FY(M)= 0.0                     FZ(M)= 0.568530273E 01
      X(M)= 0.883713672E 04        Y(M)=-0.137770117E 05          Z(M)= 0.813600159E 02
      ST(M)= 0.106570386E 04         B(M)= 0.153135815E 04
      RX(M)= 0.0                     RY(M)= 0.106433496E 04         RZ(M)= 0.540116272E 02

   SEGEMENT NUMBER= 2
      FX(M)= 0.0                     FY(M)= 0.0                     FZ(M)= 0.568530273E 01
      X(M)= 0.883713672E 04        Y(M)=-0.122472266E 05          Z(M)= 0.150820023E 03
      ST(M)= 0.106543066E 04         B(M)= 0.153135669E 04
      RX(M)= 0.0                     RY(M)= 0.106433496E 04         RZ(M)= 0.483263245E 02

   SEGEMENT NUMBER= 3
      FX(M)= 0.0                     FY(M)= 0.0                     FZ(M)= 0.568530273E 01
      X(M)= 0.883713672E 04        Y(M)=-0.107170937E 05          Z(M)= 0.212122421E 03
      ST(M)= 0.106518823E 04         B(M)= 0.153135669E 04
      RX(M)= 0.0                     RY(M)= 0.106433496E 04         RZ(M)= 0.426410217E 02

   SEGEMENT NUMBER= 4
      FX(M)= 0.0                     FY(M)= 0.0                     FZ(M)= 0.568530273E 01
      X(M)= 0.883713672E 04        Y(M)=-0.918665625E 04          Z(M)= 0.265261963E 03
      ST(M)= 0.106497559E 04         B(M)= 0.153135669E 04
      RX(M)= 0.0                     RY(M)= 0.106433496E 04         RZ(M)= 0.369557190E 02

   SEGEMENT NUMBER= 5
      FX(M)= 0.0                     FY(M)= 0.0                     FZ(M)= 0.568530273E 01
      X(M)= 0.883713672E 04        Y(M)=-0.765595703E 04          Z(M)= 0.310234131E 03
      ST(M)= 0.106479321E 04         B(M)= 0.153135669E 04
      RX(M)= 0.0                     RY(M)= 0.106433496E 04         RZ(M)= 0.312704163E 02

   SEGEMENT NUMBER= 6
      FX(M)= 0.0                     FY(M)= 0.0                     FZ(M)= 0.568530273E 01
      X(M)= 0.883713672E 04        Y(M)=-0.612503906E 04          Z(M)= 0.347035156E 03
      ST(M)= 0.106464160E 04         B(M)= 0.153135669E 04
      RX(M)= 0.0                     RY(M)= 0.106433496E 04         RZ(M)= 0.255851135E 02

   SEGEMENT NUMBER= 7
      FX(M)= 0.0                     FY(M)= 0.0                     FZ(M)= 0.568530273E 01
      X(M)= 0.883713672E 04        Y(M)=-0.459394922E 04          Z(M)= 0.375661621E 03
      ST(M)= 0.106452051E 04         B(M)= 0.153135669E 04
      RX(M)= 0.0                     RY(M)= 0.106433496E 04         RZ(M)= 0.198998108E 02

   SEGEMENT NUMBER= 8
      FX(M)= 0.0                     FY(M)= 0.0                     FZ(M)= 0.568530273E 01
      X(M)= 0.883713672E 04        Y(M)=-0.306272852E 04          Z(M)= 0.396111328E 03
      ST(M)= 0.106442920E 04         B(M)= 0.153135669E 04
      RX(M)= 0.0                     RY(M)= 0.106433496E 04         RZ(M)= 0.142145081E 02

   SEGEMENT NUMBER= 9
      FX(M)= 0.0                     FY(M)= 0.0                     FZ(M)= 0.568530273E 01
      X(M)= 0.883713672E 04        Y(M)=-0.153142041E 04          Z(M)= 0.408382568E 03
      ST(M)= 0.106436816E 04         B(M)= 0.153135669E 04
      RX(M)= 0.0                     RY(M)= 0.106433496E 04         RZ(M)= 0.852920532E 01
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SEGEMENT NUMBER=10
      FX(M)= 0.0                    FY(M)= 0.0                    FZ(M)= 0.568530273E 01
      X(M)= 0.883713672E 04        Y(M)=-0.688476563E-01         Z(M)= 0.412474121E 03
      ST(M)= 0.106433813E 04        B(M)= 0.153135669E 04
      RX(M)= 0.0                    RY(M)= 0.106433496E 04        RZ(M)= 0.284390259E 01

SEGEMENT NUMBER=11
      FX(M)= 0.0                    FY(M)= 0.0                    FZ(M)= 0.568530273E 01
      X(M)= 0.883713672E 04        Y(M)= 0.153128271E 04         Z(M)= 0.408385742E 03
      ST(M)= 0.106433813E 04        B(M)= 0.153135669E 04
      RX(M)= 0.0                    RY(M)= 0.106433496E 04        RZ(M)=-0.284140015E 01

SEGEMENT NUMBER=12
      FX(M)= 0.0                    FY(M)= 0.0                    FZ(M)= C.568530273E 01
      X(M)= C.883713672E 04        Y(M)= 0.306259082E 04         Z(M)= 0.396117920E 03
      ST(M)= 0.106436816E 04        B(M)= 0.153135669E 04
      RX(M)= 0.0                    RY(M)= 0.106433496E 04        RZ(M)=-0.852670288E 01

SEGEMENT NUMBER=13
      FX(M)= 0.0                    FY(M)= 0.0                    FZ(M)= 0.568530273E 01
      X(M)= C.883713672E C4        Y(M)= 0.459380859E 04         Z(M)= 0.375671387E 03
      ST(M)= 0.106442896E 04        B(M)= 0.153135669E 04
      RX(M)= 0.0                    RY(M)= 0.106433496F 04        RZ(M)=-0.142120056E 02

SEGEMENT NUMBER=14
      FX(M)= 0.0                    FY(M)= 0.0                    FZ(M)= 0.568530273E 01
      X(M)= 0.883713672E 04        Y(M)= 0.612489844E 04         Z(M)= 0.347048096E 03
      ST(M)= 0.106452002E 04        B(M)= 0.153135669E 04
      RX(M)= 0.0                    RY(M)= 0.106433496E 04        RZ(M)=-0.198973083E 02

SEGEMENT NUMBER=15
      FX(M)= 0.0                    FY(M)= 0.0                    FZ(M)= 0.568530273E 01
      X(M)= C.883713672E 04        Y(M)= 0.765581250E 04         Z(M)= C.310250488E 03
      ST(M)= 0.106464160E 04        B(M)= 0.153135669E 04
      RX(M)= 0.0                    RY(M)= 0.106433496E 04        RZ(M)=-0.255826111E 02

SEGEMENT NUMBER=16
      FX(M)= 0.0                    FY(M)= 0.0                    FZ(M)= 0.568530273E 01
      X(M)= C.883713672E 04        Y(M)= 0.918650781E 04         Z(M)= 0.265281738E 03
      ST(M)= C.106479321E 04        B(M)= 0.153135669E 04
      RX(M)= 0.0                    RY(M)= 0.106433496E 04        RZ(M)=-0.312679138E 02

SEGEMENT NUMBER=17
      FX(M)= 0.0                    FY(M)= 0.0                    FZ(M)= 0.568530273E 01
      X(M)= C.883713672E 04        Y(M)= 0.107169414E 05         Z(M)= 0.212145737E 03
      ST(M)= 0.106497559E 04        B(M)= 0.153135669E 04
      RX(M)= 0.0                    RY(M)= 0.106433496E 04        RZ(M)=-0.369532166E 02

SEGEMENT NUMBER=18
      FX(M)= 0.0                    FY(M)= 0.0                    FZ(M)= 0.568530273E 01
      X(M)= 0.883713672E 04        Y(M)= 0.122470703E 05         Z(M)= 0.150846939E 03
      ST(M)= 0.106518823E 04        B(M)= 0.153135669E 04
      RX(M)= 0.0                    RY(M)= 0.106433496E 04        RZ(M)=-0.426385193E 02

SEGEMENT NUMBER=19
      FX(M)= 0.0                    FY(M)= 0.0                    FZ(M)= 0.568530273E 01
      X(M)= 0.883713672E C4        Y(M)= 0.137768516E 05         Z(M)= 0.813905334E 02
      ST(M)= 0.106543066E 04        B(M)= 0.153135669E 04
      RX(M)= C.0                    RY(M)= 0.106433496E 04        RZ(M)=-0.483238220E 02

SEGEMENT NUMBER=20
      FX(M)= 0.0                    FY(M)= 0.106433496E 04        FZ(M)=-0.540091248E 02
      X(M)= 0.883713672E 04        Y(M)= 0.153062422E 05         Z(M)= 0.378234863E 01
      ST(M)= 0.106570337E 04        B(M)= 0.153135815E 04
      RX(M)= 0.0                    RY(M)= 0.106433496E C4        RZ(M)=-0.540091248E 02
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EQUILIBRIUM POSITION UNDER GRAVITY FORCES

      E=      0.185456514        DELTA= 0.187968135E 00          NO.OF ERROR LOOPS=     41

   CABLE NUMBER= 1

      SEGMENT NUMBER= 1
         FX(M,N)= 0.0                    FY(M,N)= 0.0                    FZ(M,N)=-0.128710937E 01
         X(M,N)=-0.176744727E 05         Y(M,N)= 0.0                     Z(M,N)= 0.358253860E 01
          T(M,N)= 0.122939648E 05        BL(M,N)= 0.502706520E 01
         RX(M,N)= 0.862446094E 04        RY(M,N)= 0.0                    RZ(M,N)= 0.876129687E 04

      SEGMENT NUMBER= 2
         FX(M,N)= 0.0                    FY(M,N)= 0.0                    FZ(M,N)= 0.455810547E 00
         X(M,N)=-0.167928906E 05         Y(M,N)= 0.0                     Z(M,N)= 0.899281982E 03
          T(M,N)= 0.122948828E 05        BL(M,N)= 0.125676611E 04
         RX(M,N)= 0.862446094E 04        RY(M,N)= 0.0                    RZ(M,N)= 0.876258594E 04

      SEGMENT NUMBER= 3
         FX(M,N)= 0.0                    FY(M,N)= 0.0                    FZ(M,N)= 0.455810547E 00
         X(M,N)=-0.159112852E 05         Y(M,N)= 0.0                     Z(M,N)= 0.179495801E 04
          T(M,N)= 0.122945625E 05        BL(M,N)= 0.125676611E 04
         RX(M,N)= 0.862446094E 04        RY(M,N)= 0.0                    RZ(M,N)= 0.876213281E 04

      SEGMENT NUMBER= 4
         FX(M,N)= 0.0                    FY(M,N)= 0.0                    FZ(M,N)= 0.455810547E 00
         X(M,N)=-0.150296562E 05         Y(M,N)= 0.0                     Z(M,N)= 0.269061133E 04
          T(M,N)= 0.122942383E 05        BL(M,N)= 0.125676611E 04
         RX(M,N)= 0.862446094E 04        RY(M,N)= 0.0                    RZ(M,N)= 0.876167969E 04

      SEGMENT NUMBER= 5
         FX(M,N)= 0.0                    FY(M,N)= 0.0                    FZ(M,N)= 0.455810547E 00
         X(M,N)=-0.141480039E 05         Y(M,N)= 0.0                     Z(M,N)= 0.358624219E 04
          T(M,N)= 0.122939141E 05        BL(M,N)= 0.125676611E 04
         RX(M,N)= 0.862446094E 04        RY(M,N)= 0.0                    RZ(M,N)= 0.876122656E 04

      SEGMENT NUMBER= 6
         FX(M,N)= 0.0                    FY(M,N)= 0.0                    FZ(M,N)= 0.455810547E 00
         X(M,N)=-0.132663281E 05         Y(M,N)= 0.0                     Z(M,N)= 0.448184766E 04
          T(M,N)= 0.122935937E 05        BL(M,N)= 0.125676611E 04
         RX(M,N)= 0.862446094E 04        RY(M,N)= 0.0                    RZ(M,N)= 0.876077344E 04

      SEGMENT NUMBER= 7
         FX(M,N)= 0.0                    FY(M,N)= 0.0                    FZ(M,N)= 0.455810547E 00
         X(M,N)=-0.123846289E 05         Y(M,N)= 0.0                     Z(M,N)= 0.537742969E 04
          T(M,N)= 0.122932695E 05        BL(M,N)= 0.125676611E 04
         RX(M,N)= 0.862446094E 04        RY(M,N)= 0.0                    RZ(M,N)= 0.876032031E 04

      SEGMENT NUMBER= 8
         FX(M,N)= 0.0                    FY(M,N)= 0.0                    FZ(M,N)= 0.455810547E 00
         X(M,N)=-0.115029102E 05         Y(M,N)= 0.0                     Z(M,N)= 0.627298828E 04
          T(M,N)= 0.122929453E 05        BL(M,N)= 0.125676409E 04
         RX(M,N)= 0.862446094E 04        RY(M,N)= 0.0                    RZ(M,N)= 0.875986719E 04

      SEGMENT NUMBER= 9
         FX(M,N)= 0.0                    FY(M,N)= 0.0                    FZ(M,N)= 0.191687012E 03
         X(M,N)=-0.106211680E 05         Y(M,N)= 0.0                     Z(M,N)= 0.716852344E 04
          T(M,N)= 0.122926290E 05        BL(M,N)= 0.125676409E 04
         RX(M,N)= 0.862446094E 04        RY(M,N)= 0.0                    RZ(M,N)= 0.879941406E 04

      SEGMENT NUMBER=10
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FX(M,N)= 0.0                      FY(M,N)= 0.0                      FZ(M,N)= 0.394067383E 01
X(M,N)=-0.804164844E 04           Y(M,N)= 0.0                       Z(M,N)= 0.093633594E 04
 T(M,N)= 0.121567773E 05          BL(M,N)= 0.250835547E 04
RX(M,N)= 0.862446094E 04          RY(M,N)= 0.0                      RZ(M,N)= 0.856773047E 04

SEGMENT NUMBER=11
FX(M,N)= 0.0                      FY(M,N)= 0.0                      FZ(M,N)=-0.187290527E 03
X(M,N)=-0.706172656E 04           Y(M,N)= 0.0                       Z(M,N)= 0.107037344E 05
 T(M,N)= 0.121540039E 05          BL(M,N)= 0.250835083E 04
RX(M,N)= 0.862446094E 04          RY(M,N)= 0.0                      RZ(M,N)= 0.856379297E 04

SEGMENT NUMBER=12
FX(M,N)= 0.0                      FY(M,N)= 0.0                      FZ(M,N)= 0.455810547E 00
X(M,N)=-0.617955859E 04           Y(M,N)= 0.0                       Z(M,N)= 0.115988516E 05
 T(M,N)= 0.122866914E 05          BL(M,N)= 0.125676270E 04
RX(M,N)= 0.862446094E 04          RY(M,N)= 0.0                      RZ(M,N)= 0.875108594E 04

SEGMENT NUMBER=13
FX(M,N)= 0.0                      FY(M,N)= 0.0                      FZ(M,N)= 0.455810547E 00
X(M,N)=-0.529736719E 04           Y(M,N)= 0.0                       Z(M,N)= 0.124939453E 05
 T(M,N)= 0.122863672E 05          BL(M,N)= 0.125676147E 04
RX(M,N)= 0.862446094E 04          RY(M,N)= 0.0                      RZ(M,N)= 0.875063281E 04

SEGMENT NUMBER=14
FX(M,N)= 0.0                      FY(M,N)= 0.0                      FZ(M,N)= 0.455810547E 00
X(M,N)=-0.441515234E 04           Y(M,N)= 0.0                       Z(M,N)= 0.133890156E 05
 T(M,N)= 0.122860430E 05          BL(M,N)= 0.125676147E 04
RX(M,N)= 0.862446094E 04          RY(M,N)= 0.0                      RZ(M,N)= 0.875017969E 04

SEGMENT NUMBER=15
FX(M,N)= 0.0                      FY(M,N)= 0.0                      FZ(M,N)= 0.455810547E 00
X(M,N)=-0.353291797E 04           Y(M,N)= 0.0                       Z(M,N)= 0.142840625E 05
 T(M,N)= 0.122857227E 05          BL(M,N)= 0.125676147E 04
RX(M,N)= 0.862446094E 04          RY(M,N)= 0.0                      RZ(M,N)= 0.874972656E 04

SEGMENT NUMBER=16
FX(M,N)= 0.0                      FY(M,N)= 0.0                      FZ(M,N)= 0.455810547E 00
X(M,N)=-0.265066040E 04           Y(M,N)= 0.0                       Z(M,N)= 0.151790859E 05
 T(M,N)= 0.122853984E 05          BL(M,N)= 0.125676147E 04
RX(M,N)= 0.862446094E 04          RY(M,N)= 0.0                      RZ(M,N)= 0.874927344E 04

SEGMENT NUMBER=17
FX(M,N)= 0.0                      FY(M,N)= 0.0                      FZ(M,N)= 0.455810547E 00
X(M,N)=-0.176837988E 04           Y(M,N)= 0.0                       Z(M,N)= 0.160740859E 05
 T(M,N)= 0.122850781E 05          BL(M,N)= 0.125676147E 04
RX(M,N)= 0.862446094E 04          RY(M,N)= 0.0                      RZ(M,N)= 0.874882031E 04

SEGMENT NUMBER=18
FX(M,N)= 0.0                      FY(M,N)= 0.0                      FZ(M,N)= 0.455810547E 00
X(M,N)=-0.886076172E 03           Y(M,N)= 0.0                       Z(M,N)= 0.169690625E 05
 T(M,N)= 0.122847539E 05          BL(M,N)= 0.125676147E 04
RX(M,N)= 0.862446094E 04          RY(M,N)= 0.0                      RZ(M,N)= 0.874836719E 04

SEGMENT NUMBER=19
FX(M,N)= 0.0                      FY(M,N)= 0.0                      FZ(M,N)=-0.128697205E 01
X(M,N)=-0.374926758E 01           Y(M,N)= 0.0                       Z(M,N)= 0.178640156E 05
 T(M,N)= 0.122844336E 05          BL(M,N)= 0.125676147E 04
RX(M,N)= 0.862446094E 04          RY(M,N)= 0.0                      RZ(M,N)= 0.874791406E 04

SEGMENT NUMBER=20
FX(M,N)= 0.0                      FY(M,N)= 0.0                      FZ(M,N)= 0.260954531E 05
X(M,N)=-0.220222473E 00           Y(M,N)= 0.0                       Z(M,N)= 0.178675937E 05
 T(M,N)= 0.122853477E 05          BL(M,N)= 0.502704620E 01
RX(M,N)= 0.862446094E 04          RY(M,N)= 0.0                      RZ(M,N)= 0.874920312E 04
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EQUILIBRIUM POSITION UNDER ACTING FORCES

E= 0.861418247E-01          DELTA= 0.187968135E 00
   NO. OF ERROR LOOPS=    24              NO. OF ACCURACY LOOPS=     1
     CURRENT ANGLE=   0.0

CABLE NUMBER= 1

  SEGMENT NUMBER= 1
       FX(M,N)= 0.194408875E 02         FY(M,N)=-0.824408358E-13          FZ(M,N)=-0.860163307E 01
       X(M,N)=-0.176743672E 05          Y(M,N)=-0.258167172E-15          Z(M,N)= 0.348359013E 01
        T(M,N)= 0.144679820E 05         BL(M,N)= 0.503184795E 01
       RX(M,N)= 0.104394727E 05         RY(M,N)=-0.742257655E-12          RZ(M,N)= 0.100156836E 05
           HORIZL(M,N)= 0.105468750E 00          HEIGHT(M,N)=-0.989484787E-01

  SEGMENT NUMBER= 2
       FX(M,N)= 0.388785095E 02         FY(M,N)=-0.148983419E-12          FZ(M,N)=-0.141364994E 02
       X(M,N)=-0.167678047E 05          Y(M,N)=-0.576632383E-13          Z(M,N)= 0.875611816E 03
        T(M,N)= 0.144590234E 05         BL(M,N)= 0.125795825E 04
       RX(M,N)= 0.104290352E 05         RY(M,N)=-0.659816819E-12          RZ(M,N)= 0.100242852E 05
           HORIZL(M,N)= 0.250859222E 02          HEIGHT(M,N)=-0.236701660E 02

  SEGMENT NUMBER= 3
       FX(M,N)= 0.389928589E 02         FY(M,N)=-0.120818069E-12          FZ(M,N)=-0.141793261E 02
       X(M,N)=-0.158634961E 05          Y(M,N)=-0.102162040E-12          Z(M,N)= 0.175006152E 04
        T(M,N)= 0.144408555E 05         BL(M,N)= 0.125794751E 04
       RX(M,N)= 0.103811602E 05         RY(M,N)=-0.510833400E-12          RZ(M,N)= 0.100384219E 05
           HORIZL(M,N)= 0.477890472E 02          HEIGHT(M,N)=-0.448964844E 02

  SEGMENT NUMBER= 4
       FX(M,N)= 0.391081848E 02         FY(M,N)=-0.968125862E-13          FZ(M,N)=-0.142219162E 02
       X(M,N)=-0.149614609E 05          Y(M,N)=-0.136178829E-12          Z(M,N)= 0.262684033E 04
        T(M,N)= 0.144227305E 05         BL(M,N)= 0.125793799E 04
       RX(M,N)= 0.103421680E 05         RY(M,N)=-0.390015331E-12          RZ(M,N)= 0.100526016E 05
           HORIZL(M,N)= 0.681952820E 02          HEIGHT(M,N)=-0.637709961E 02

  SEGMENT NUMBER= 5
       FX(M,N)= 0.392243958E 02         FY(M,N)=-0.765490644E-13          FZ(M,N)=-0.142642326E 02
       X(M,N)=-0.140617148E 05          Y(M,N)=-0.161783564E-12          Z(M,N)= 0.350595483E 04
        T(M,N)= 0.144046523E 05         BL(M,N)= 0.125792847E 04
       RX(M,N)= 0.103030625E 05         RY(M,N)=-0.293202745E-12          RZ(M,N)= 0.100668242E 05
           HORIZL(M,N)= 0.862890472E 02          HEIGHT(M,N)=-0.802873535E 02

  SEGMENT NUMBER= 6
       FX(M,N)= 0.393415985E 02         FY(M,N)=-0.596282464E-13          FZ(M,N)=-0.143062744E 02
       X(M,N)=-0.131642773E 05          Y(M,N)=-0.180727015E-12          Z(M,N)= 0.438741016E 04
        T(M,N)= 0.143866172E 05         BL(M,N)= 0.125791772E 04
       RX(M,N)= 0.102638398E 05         RY(M,N)=-0.216653681E-12          RZ(M,N)= 0.100810898E 05
           HORIZL(M,N)= 0.102050766E 03          HEIGHT(M,N)=-0.944375000E 02

  SEGMENT NUMBER= 7
       FX(M,N)= 0.394598236E 02         FY(M,N)=-0.456703800E-13          FZ(M,N)=-0.143480864E 02
       X(M,N)=-0.122691680E 05          Y(M,N)=-0.194473832E-12          Z(M,N)= 0.527121484E 04
        T(M,N)= 0.143686250E 05         BL(M,N)= 0.125790820E 04
       RX(M,N)= 0.102245000E 05         RY(M,N)=-0.157025434E-12          RZ(M,N)= 0.100953984E 05
           HORIZL(M,N)= 0.115460922E 03          HEIGHT(M,N)=-0.106214844E 03

  SEGMENT NUMBER= 8
       FX(M,N)= 0.395790605E 02         FY(M,N)=-0.343150059E-13          FZ(M,N)=-0.143896065E 02
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     X(M,N)= 0.113764C23E 05         Y(M,N)=-0.204234524E-12         Z(M,N)= 0.615737500E 04
      T(M,N)= 0.143506836E 05         BL(M,N)= 0.125789860E 04
     RX(M,N)= 0.101850430E 05         RY(M,N)=-0.111355098E-12         RZ(M,N)= 0.101097500E 05
          HORIZL(M,N)= 0.126507797E 03          HEIGHT(M,N)=-0.115613281E 03

SEGMENT NUMBER= 9
     FX(M,N)= 0.651191406E 02         FY(M,N)=-0.331442332E-13         FZ(M,N)= 0.169500488E 03
     X(M,N)=-0.104860039E 05         Y(M,N)=-0.210995772E-12         Z(M,N)= 0.704589844E 04
      T(M,N)= 0.143327812E 05         BL(M,N)= 0.125788794E 04
     RX(M,N)= 0.101454648E 05         RY(M,N)=-0.770400996E-13         RZ(M,N)= 0.101241406E 05
          HORIZL(M,N)= 0.135164047E 03          HEIGHT(M,N)=-0.127625000E 03

SEGMENT NUMBER=10
     FX(M,N)= 0.789769135E 02         FY(M,N)=-0.270671038E-13         FZ(M,N)=-0.256478119E 02
     X(M,N)=-0.869966406E 04         Y(M,N)=-0.218774543E-12         Z(M,N)= 0.880996094E 04
      T(M,N)= 0.141671523E 05         BL(M,N)= 0.251056372E 04
     RX(M,N)= 0.100803477E 05         RY(M,N)=-0.438958867E-13         RZ(M,N)= 0.995464067E 04
          HORIZL(M,N)= 0.141984360E 03          HEIGHT(M,N)=-0.126375000E 03

SEGMENT NUMBER=11
     FX(M,N)= 0.537936401E 02         FY(M,N)=-0.105087820E-13         FZ(M,N)=-0.209656509E 03
     X(M,N)=-0.692258594E 04         Y(M,N)=-0.221764718E-12         Z(M,N)= 0.105832930E 05
      T(M,N)= 0.141291719E 05         BL(M,N)= 0.251052075E 04
     RX(M,N)= 0.100013711E 05         RY(M,N)=-0.168287828E-13         RZ(M,N)= 0.998028906E 04
          HORIZL(M,N)= 0.139140610E 03          HEIGHT(M,N)=-0.120441406E 03

SEGMENT NUMBER=12
     FX(M,N)= 0.402956696E 02         FY(M,N)=-0.309717322E-14         FZ(M,N)=-0.146258202E 02
     X(M,N)=-0.604392578E 04         Y(M,N)=-0.222372920E-12         Z(M,N)= 0.114833555E 05
      T(M,N)= 0.142404102E 05         BL(M,N)= 0.125783789E 04
     RX(M,N)= 0.994757812E 04         RY(M,N)=-0.632000081E-14         RZ(M,N)= 0.101899492E 05
          HORIZL(M,N)= 0.135632797E 03          HEIGHT(M,N)=-0.115496094E 03

SEGMENT NUMBER=13
     FX(M,N)= 0.404218292E 02         FY(M,N)=-0.173420827E-14         FZ(M,N)=-0.146650953E 02
     X(M,N)=-0.516775000E 04         Y(M,N)=-0.222607902E-12         Z(M,N)= 0.123858203E 05
      T(M,N)= 0.142227852E 05         BL(M,N)= 0.125782837E 04
     RX(M,N)= 0.990728516E 04         RY(M,N)=-0.322283056E-14         RZ(M,N)= 0.102045781E 05
          HORIZL(M,N)= 0.129617172E 03          HEIGHT(M,N)=-0.108125000E 03

SEGMENT NUMBER=14
     FX(M,N)= 0.405489960E 02         FY(M,N)=-0.884906755E-15         FZ(M,N)=-0.147039843E 02
     X(M,N)=-0.429407422E 04         Y(M,N)=-0.222739687E-12         Z(M,N)= 0.132906914E 05
      T(M,N)= 0.142052109E 05         BL(M,N)= 0.125781763E 04
     RX(M,N)= 0.986686719E 04         RY(M,N)=-0.148862229E-14         RZ(M,N)= 0.102192461E 05
          HORIZL(M,N)= 0.121078110E 03          HEIGHT(M,N)=-0.983242188E 02

SEGMENT NUMBER=15
     FX(M,N)= 0.406771240E 02         FY(M,N)=-0.398635304E-15         FZ(M,N)=-0.147424345E 02
     X(M,N)=-0.342292261E 04         Y(M,N)=-0.222793192E-12         Z(M,N)= 0.141979805E 05
      T(M,N)= 0.141876797E 05         BL(M,N)= 0.125780811E 04
     RX(M,N)= 0.982632031E 04         RY(M,N)=-0.603715533E-15         RZ(M,N)= 0.102339531E 05
          HORIZL(M,N)= 0.109995346E 03          HEIGHT(M,N)=-0.860820313E 02

SEGMENT NUMBER=16
     FX(M,N)= 0.408062744E 02         FY(M,N)=-0.151004256E-15         FZ(M,N)=-0.147804918E 02
     X(M,N)=-0.255431372E 04         Y(M,N)=-0.222811353E-12         Z(M,N)= 0.151076914E 05
      T(M,N)= 0.141701992E 05         BL(M,N)= 0.125779858E 04
     RX(M,N)= 0.978564453E 04         RY(M,N)=-0.205080256E-15         RZ(M,N)= 0.102486992E 05
          HORIZL(M,N)= 0.963466644E 02          HEIGHT(M,N)=-0.713945313E 02

SEGMENT NUMBER=17
     FX(M,N)= 0.409364319E 02         FY(M,N)=-0.444461481E-16         FZ(M,N)=-0.148181152E 02
     X(M,N)=-0.168826807E 04         Y(M,N)=-0.222816123E-12         Z(M,N)= 0.160198281E 05
      T(M,N)= 0.141527695E 05         BL(M,N)= 0.125778906E 04
     RX(M,N)= 0.974483984E 04         RY(M,N)=-0.540759995E-16         RZ(M,N)= 0.102634805E 05
```

```
      HORIZL(M,N)= 0.801118011E 02          HEIGHT(M,N)=-0.542578125E 02

  SEGMENT NUMBER=18
     FX(M,N)= 0.410677338E 02           FY(M,N)=-0.881786444E-17           FZ(M,N)=-0.148553724E 02
      X(M,N)=-0.824806396E 03          Y(M,N)=-0.222816936E-12           Z(M,N)= 0.169343984E 05
       T(M,N)= 0.141353867E 05          BL(M,N)= 0.125777955E 04
     RX(M,N)= 0.970390625E 04          RY(M,N)=-0.962985554E-17           RZ(M,N)= 0.102783008E 05
         HORIZL(M,N)= 0.612697601E 02          HEIGHT(M,N)=-0.344640625E 02

  SEGMENT NUMBER=19
     FX(M,N)= 0.206017761E 02           FY(M,N)=-0.811991095E-18           FZ(M,N)=-0.898250580E 01
      X(M,N)= 0.360505371E 02          Y(M,N)=-0.222816991E-12           Z(M,N)= 0.178514062E 05
       T(M,N)= 0.141180547E 05          BL(M,N)= 0.125777002E 04
     RX(M,N)= 0.966283984E 04          RY(M,N)=-0.811991095E-18           RZ(M,N)= 0.102931562E 05
         HORIZL(M,N)= 0.397997894E 02          HEIGHT(M,N)=-0.126093750E 02

  SEGMENT NUMBER=20
     FX(M,N)= 0.531686279E 03           FY(M,N)= 0.0                       FZ(M,N)= 0.260954648E 05
      X(M,N)= 0.394884338E 02          Y(M,N)=-0.222816991E-12           Z(M,N)= 0.178550781E 05
       T(M,N)= 0.141105195E 05          BL(M,N)= 0.503106594E 01
     RX(M,N)= 0.964223828E 04          RY(M,N)= 0.0                       RZ(M,N)= 0.103021406E 05
         HORIZL(M,N)= 0.397086334E 02          HEIGHT(M,N)=-0.125156250E 02

CABLE NUMBER= 2

  SEGMENT NUMBER= 1
     FX(M,N)= 0.288327332E 02           FY(M,N)= 0.465512848E 01           FZ(M,N)= 0.411708439E 01
      X(M,N)= 0.415003204E 02          Y(M,N)=-0.300659466E 01           Z(M,N)= 0.178515898E 05
       T(M,N)= 0.113775664E 05          BL(M,N)= 0.502504826E 01
     RX(M,N)= 0.455527734E 04          RY(M,N)=-0.680744531E 04           RZ(M,N)=-0.789666016E 04
         HORIZL(M,N)= 0.399482880E 02          HEIGHT(M,N)=-0.124375000E 02

  SEGMENT NUMBER= 2
     FX(M,N)= 0.576410980E 02           FY(M,N)= 0.923836136E 01           FZ(M,N)= 0.111710978E 02
      X(M,N)= 0.541546875E 03          Y(M,N)=-0.755554688E 03           Z(M,N)= 0.169787734E 05
       T(M,N)= 0.113717031E 05          BL(M,N)= 0.125625930E 04
     RX(M,N)= 0.452644531E 04          RY(M,N)=-0.681210156E 04           RZ(M,N)=-0.790077344E 04
         HORIZL(M,N)= 0.980391541E 02          HEIGHT(M,N)= 0.583203125E 01

  SEGMENT NUMBER= 3
     FX(M,N)= 0.578617056E 02           FY(M,N)= 0.916803265E 01           FZ(M,N)= 0.110901337E 02
      X(M,N)= 0.103563672E 04          Y(M,N)=-0.150975073E 04           Z(M,N)= 0.161039922E 05
       T(M,N)= 0.113622031E 05          BL(M,N)= 0.125625366E 04
     RX(M,N)= 0.446880469E 04          RY(M,N)=-0.682133984E 04           RZ(M,N)=-0.791194531E 04
         HORIZL(M,N)= 0.150552734E 03          HEIGHT(M,N)= 0.221601563E 02

  SEGMENT NUMBER= 4
     FX(M,N)= 0.580816345E 02           FY(M,N)= 0.909574318E 01           FZ(M,N)= 0.110069008E 02
      X(M,N)= 0.152372949E 04          Y(M,N)=-0.226558008E 04           Z(M,N)= 0.152272656E 05
       T(M,N)= 0.113528320E 05          BL(M,N)= 0.125624756E 04
     RX(M,N)= 0.441094531E 04          RY(M,N)=-0.683050781E 04           RZ(M,N)=-0.792303906E 04
         HORIZL(M,N)= 0.196960144E 03          HEIGHT(M,N)= 0.365625000E 02

  SEGMENT NUMBER= 5
     FX(M,N)= 0.583007355E 02           FY(M,N)= 0.902149105E 01           FZ(M,N)= 0.109213705E 02
      X(M,N)= 0.200578711E 04          Y(M,N)=-0.302303125E 04           Z(M,N)= 0.143486094E 05
       T(M,N)= 0.113435742E 05          BL(M,N)= 0.125624292E 04
     RX(M,N)= 0.435286719E 04          RY(M,N)=-0.683960547E 04           RZ(M,N)=-0.793404687E 04
         HORIZL(M,N)= 0.237160553E 03          HEIGHT(M,N)= 0.490625000E 02

  SEGMENT NUMBER= 6
     FX(M,N)= 0.585189056E 02           FY(M,N)= 0.894524097E 01           FZ(M,N)= 0.108335400E 02
      X(M,N)= 0.248176978E 04          Y(M,N)=-0.378208960E 04           Z(M,N)= 0.134680391E 05
       T(M,N)= 0.113344414E 05          BL(M,N)= 0.125623804E 04
     RX(M,N)= 0.429457031E 04          RY(M,N)=-0.684862891E 04           RZ(M,N)=-0.794496875E 04
```

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EQUILIBRIUM POSITION UNDER ACTING FORCES

E= 0.152201653E C0          DELTA= 0.152764359E 03
   NO. OF ERROR LOOPS=  124            NO. OF ACCURACY LOOPS=   15
     CURRENT ANGLE=   0.0

CHORDAL DISTANCE BETWEEN END POINTS= 0.306108203E 05

SEGEMENT NUMBER= 1
    FX(M)= 0.701773834E 02           FY(M)=-0.573586559E 01           FZ(M)= 0.563404465E 01
    X(M)= C.901807472E 04           Y(M)=-0.137815820E 05           Z(M)= 0.172642212E 02
    ST(M)= 0.572407812E 04           B(M)= 0.153449658E 04
    RX(M)= 0.671592275E 03           RY(M)= 0.568429687E 04           RZ(M)= 0.538140564E 02
         HORIZL(M)= 0.180995209E 03            HEIGHT(M)=-0.640957947E 02

SEGEMENT NUMBER= 2
    FX(M)= 0.703657074E 02           FY(M)=-0.511111546E 01           FZ(M)= 0.564462948E 01
    X(M)= 0.917935547E 04           Y(M)=-0.122556406E 05           Z(M)= 0.301850281E 02
    ST(M)= 0.572192969E 04           B(M)= 0.153449512E 04
    RX(M)= 0.601405029E 03           RY(M)= 0.569003516F C4           RZ(M)= 0.481800232E 02
         HORIZL(M)= 0.342322021E 03            HEIGHT(M)=-0.120634995E 03

SEGEMENT NUMBER= 3
    FX(M)= 0.705310059E 02           FY(M)=-0.448180389E 01           FZ(M)= 0.565403175E 01
    X(M)= 0.932181250E 04           Y(M)=-0.107278125E 05           Z(M)= 0.415959015E 02
    ST(M)= 0.572000781E 04           B(M)= 0.153449512E C4
    RX(M)= 0.531039551E 03           RY(M)= 0.569514844E 04           RZ(M)= 0.425354004E 02
         HORIZL(M)= 0.484794189E 03            HEIGHT(M)=-0.170526520E 03

SEGEMENT NUMBER= 4
    FX(M)= 0.706727600E 02           FY(M)=-0.384846115E 01           FZ(M)= 0.566222763E 01
    X(M)= C.944538672E 04           Y(M)=-0.919833203E 04           Z(M)= 0.514928894E 02
    ST(M)= 0.571832422E 04           B(M)= 0.153449365E 04
    RX(M)= 0.460508545E 03           RY(M)= 0.569963281E 04           RZ(M)= 0.368813782E 02
         HORIZL(M)= 0.608361816E 03            HEIGHT(M)=-0.213769073E 03

SEGEMENT NUMBER= 5
    FX(M)= 0.707905731E 02           FY(M)=-0.321169472E 01           FZ(M)= 0.566919708E 01
    X(M)= 0.955002344E 04           Y(M)=-0.766742969E 04           Z(M)= 0.598725586E 02
    ST(M)= 0.571687109E 04           B(M)= 0.153449219E 04
    RX(M)= 0.389835938E 03           RY(M)= 0.570348437E 04           RZ(M)= 0.312191620E 02
         HORIZL(M)= 0.712979760E 03            HEIGHT(M)=-C.250361572E 03

SEGEMENT NUMBER= 6
    FX(M)= 0.708841248E 02           FY(M)=-0.257212257E C1           FZ(M)= 0.567492199E 01
    X(M)= 0.963567578E 04           Y(M)=-0.613534375E 04           Z(M)= 0.667319794E 02
    ST(M)= 0.571566406E 04           B(M)= 0.153449219E 04
    RX(M)= 0.319045410E 03           RY(M)= 0.570669922E 04           RZ(M)= 0.255499725E 02
         HORIZL(M)= 0.798605469E 03            HEIGHT(M)=-0.280302979E 03

SEGEMENT NUMBER= 7
    FX(M)= 0.709535065E 02           FY(M)=-0.193030548E 01           FZ(M)= 0.567938805E 01
    X(M)= 0.970230859E C4           Y(M)=-0.460230859E 04           Z(M)= 0.720687561E 02
    ST(M)= 0.571469531E 04           B(M)= 0.153449072E 04
    RX(M)= 0.248161331E 03           RY(M)= 0.570927344E 04           RZ(M)= 0.198750610E 02
         HORIZL(M)= 0.865212158E 03            HEIGHT(M)=-0.303592773E 03

SEGEMENT NUMBER= 8
    FX(M)= 0.709983978E 02           FY(M)=-0.128673077E 01           FZ(M)= 0.568258476E 01
    X(M)= 0.974989453E 04           Y(M)=-0.306855981E 04           Z(M)= 0.758810120E 02
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    ST(M)= 0.571396875E 04          B(M)= 0.153449072E 04
    RX(M)= 0.177207825E 03          RY(M)= 0.571120703E 04          RZ(M)= 0.141956768E 02
         HORIZL(M)= 0.912776367E 03          HEIGHT(M)=-0.320230225E 03

 SEGEMENT NUMBER= 9
    FX(M)= 0.710187073E 02          FY(M)=-0.642094791E 00          FZ(M)= 0.568490451E 01
    X(M)= 0.977841797E 04          Y(M)=-0.153433569E 04          Z(M)= 0.781673809E 02
    ST(M)= 0.571348828E 04          B(M)= 0.153449072E 04
    RX(M)= 0.106209427E 03          RY(M)= 0.571249609E 04          RZ(M)= 0.851309204E 01
         HORIZL(M)= 0.941285645E 03          HEIGHT(M)=-0.330215088E 03

 SEGEMENT NUMBER=10
    FX(M)= 0.710144043E 02          FY(M)= 0.290662050E-02          FZ(M)= 0.568514156E 01
    X(M)= 0.978786719E 04          Y(M)= 0.124755859E 00          Z(M)= 0.789270935E 02
    ST(M)= 0.571324609E 04          B(M)= 0.153448926E 04
    RX(M)= 0.351907196E 02          RY(M)= 0.571314062E 04          RZ(M)= 0.282858753E 01
         HORIZL(M)= 0.950730225E 03          HEIGHT(M)=-0.333546875E 03

 SEGEMENT NUMBER=11
    FX(M)= 0.709854736E 02          FY(M)= 0.647774577E 00          FZ(M)= 0.568449593E 01
    X(M)= 0.977824219E 04          Y(M)= 0.153458423E 04          Z(M)= 0.781598663E 02
    ST(M)= 0.571325000E 04          B(M)= 0.153448926E 04
    RX(M)=-0.358236847E 02          RY(M)= 0.571314062E 04          RZ(M)=-0.285655403E 01
         HORIZL(M)= 0.941111084E 03          HEIGHT(M)=-0.330225830E 03

 SEGEMENT NUMBER=12
    FX(M)= 0.709319458E 02          FY(M)= 0.129194450E 01          FZ(M)= 0.568256855E 01
    X(M)= 0.974955469E 04          Y(M)= 0.306880615E 04          Z(M)= 0.758659668E 02
    ST(M)= 0.571349609E 04          B(M)= 0.153449072E 04
    RX(M)=-0.106909158E 03          RY(M)= 0.571249609E 04          RZ(M)=-0.854104996E 01
         HORIZL(M)= 0.912430965E 03          HEIGHT(M)=-0.320251953E 03

 SEGEMENT NUMBER=13
    FX(M)= 0.708537750E 02          FY(M)= 0.193472004E 01          FZ(M)= 0.567936611E 01
    X(M)= 0.970182031E 04          Y(M)= 0.460254687E 04          Z(M)= 0.720462036E 02
    ST(M)= 0.571398437E 04          B(M)= 0.153449072E 04
    RX(M)=-0.177741104E 03          RY(M)= 0.571120703E 04          RZ(M)=-0.142236185E 02
         HORIZL(M)= 0.864727539E 03          HEIGHT(M)=-0.303625000E 03

 SEGEMENT NUMBER=14
    FX(M)= 0.707513123E 02          FY(M)= 0.257547665E 01          FZ(M)= 0.567489624E 01
    X(M)= 0.963506641E 04          Y(M)= 0.613557422E 04          Z(M)= 0.667019348E 02
    ST(M)= 0.571471484E 04          B(M)= 0.153449072E 04
    RX(M)=-0.248594879E 03          RY(M)= 0.570927344E 04          RZ(M)=-0.199029846E 02
         HORIZL(M)= 0.798000977E 03          HEIGHT(M)=-0.280345947E 03

 SEGEMENT NUMBER=15
    FX(M)= 0.706249695E 02          FY(M)= 0.321372318E 01          FZ(M)= 0.566917229E 01
    X(M)= 0.954932812E 04          Y(M)= 0.766765234E 04          Z(M)= 0.598350220E 02
    ST(M)= 0.571567969E 04          B(M)= 0.153449219E 04
    RX(M)=-0.319346191E 03          RY(M)= 0.570669922E 04          RZ(M)=-0.255778809E 02
         HORIZL(M)= 0.712209551E 03          HEIGHT(M)=-0.250415466E 03

 SEGEMENT NUMBER=16
    FX(M)= 0.704747772E 02          FY(M)= 0.384884167E 01          FZ(M)= 0.566220760E 01
    X(M)= 0.944469234E 04          Y(M)= 0.919054687E 04          Z(M)= 0.514478760E 02
    ST(M)= 0.571688672E 04          B(M)= 0.153449219E 04
    RX(M)=-0.389971191E 03          RY(M)= 0.570348828E 04          RZ(M)=-0.312470551E 02
         HORIZL(M)= 0.607634766E 03          HEIGHT(M)=-0.213033862E 03

 SEGEMENT NUMBER=17
    FX(M)= 0.703011932E 02          FY(M)= 0.448022461E 01          FZ(M)= 0.565402126E 01
    X(M)=-0.932108784E 04          Y(M)= 0.107280234E 05          Z(M)= 0.415433807E 02
    ST(M)= 0.571832422E 04          B(M)= 0.153449365E 04
    RX(M)=-0.460446045E 03          RY(M)= 0.569964062E 04          RZ(M)=-0.369092712E 02
         HORIZL(M)= 0.484079834E 03          HEIGHT(M)=-0.17[illegible]E 03
```

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SEGEMENT NUMBER=18
     FX(M)= 0.701047058E 02          FY(M)= 0.510740280E 01          FZ(M)= 0.564463425E 01
     X(M)= 0.917870703E 04          Y(M)= 0.122558555E 05          Z(M)= 0.301249847E 02
     ST(M)= 0.571999609E 04          B(M)= 0.153449512E 04
     RX(M)=-C.530747314E 03          RY(M)= 0.569516406E 04          RZ(M)=-0.425632935E 02
          HORIZL(M)= 0.341683105E 03          HEIGHT(M)=-C.120721954E 03

SEGEMENT NUMBER=19
     FX(M)= 0.698954218E 02          FY(M)= 0.572977066E 01          FZ(M)= 0.563407135E 01
     X(M)= 0.901757031E 04          Y(M)= 0.137818125E 05          Z(M)= 0.171965942E 02
     ST(M)= 0.572189453E 04          B(M)= 0.153449512F 04
     RX(M)=-C.600852051E 03          RY(M)= 0.569005859E 04          RZ(M)=-0.482079315F 02
          HORIZL(M)= 0.180501770E 03          HEIGHT(M)=-0.641939392E 02

SEGEMENT NUMBER=20
     FX(M)=-C.670737549E 03          FY(M)= 0.568433203E 04          FZ(M)=-0.538420105E C2
     X(M)= 0.883775781E 04          Y(M)= 0.153056680E 05          Z(M)= 0.276261616E 01
     ST(M)= C.572401953E 04          B(M)= 0.153449658E 04
     RX(M)=-0.670737549E 03          RY(M)= 0.568433203E 04          RZ(M)=-0.538420105E C2
          HCRIZL(M)= 0.845863223E 00          HEIGHT(M)=-0.101573248E C1
```

APPENDIX II

SPECIAL FEATURES FOR USING THE COMPUTER PROGRAM

The Computer Program that has been described in Appendix I can be used by using appropriate data cards. Because of the truncation errors made by the computer it is necessary to choose the appropriate cutoff values that will suggest that the method has been used satisfactorily to simulate the cable system. A brief description of these cutoff values is made in the following paragraphs:

A. <u>Cutoff Value to Define the Acceptable Completion of Imaginary Reaction Routine</u>

As described earlier in Chapter I, the equilibrium configuration of the array system is obtained if E, the measure of error between the end coordinates, as obtained by system of forces at hand and the correct ones as specified, is zero. Theoretically, the iteration would continue until E is identically zero i.e., until the equilibrium configuration (under the constant applied forces) is obtained exactly. However, because of computer roundoff errors, it is not possible to achieve this and as such a cutoff value, that would define the acceptable completion of the imaginary reaction routine, has to be defined.

If this cutoff value is denoted by COMPE, then the imaginary reaction routine is considered to have given the satisfactory equilibrium configuration of the cable system when

$$E \leq \text{COMPE} \qquad (1,\text{II})$$

That is, when

$X_{M(n),n}$: $Y_{M(n),n}$: $Z_{M(n),n}$ for n = 2 and 3 for the main arrays and X_{MN}: Y_{MN}: Z_{MN} for the tie leg array, are all within COMPE from their true anchor values.

B. Cutoff Value to Define the Acceptable Completion of the Successive Approximation Iterations

As described in Chapter I COMPD denotes the fixed accuracy value and is used to suggest the acceptable completion of the successive approximation routine. That is, the equilibrium coordinates of any cable station for two successive iterations are compared. If the coordinates differ by less than COMPD, the iteration is considered satisfied.

However, introduction of COMPE as a cutoff value also introduces an error, again within $\sqrt{COMPE}$ from the actual equilibrium coordinates, into the coordinates calculated for every cable station. With the result, it is important that the cutoff value COMPD for the successive approximation iteration be chosen outside the value of this inherent error.

A safe minimum value for COMPD[9] is

$$COMPD = 10 \sqrt{COMPE}$$

C. Cutoff Value to Define the Acceptable Completion of the Force Balance Condition

The force balance condition, as described in Chapter IV, is said to have been satisfied if

$$FFX + RX1 = 0$$

$$FFY + RY1 = 0$$

$$FFZ + RZ1 = 0$$

where FFY and RY1 are defined by equations (1,4). FFX, FFZ and RX1, RZ1 are similar forces in the X and Z direction respectively.

However, because of computer roundoff error some cutoff value is defined which would suggest that the force balance condition has been satisfied to an acceptable degree. This value is defined by TIECOM.

TIECOM can be made very small, since binary search routine will make the values of FFY and RY1 converge to an acceptable positive number. An acceptable value for TIECOM could be 1 lb.

D. PRECISION FOCUS

This convergence concept was suggested by G. H. Savage[13] and is used in conjunction with the δ method of convergence discussed in Chapter I. It utilizes the past performance of the force and displacement to bring the cable array to the required coordinates. Referring to Figure 17, the end of the cable is released from point K' and imaginary reactions are applied at the free end. For each iteration, depending upon the position of the K end, additive forces given by equation (20,1) are added to the imaginary reactions. After a certain number of iterations, it is possible to bring the K end to its X and Z coordinates within limits of COMPE. Normally the above process would be applied until y coordinate is also within the limits of COMPE. However, it has been found that this situation is not always possible to achieve. The positive number δ often becomes too small to make any significant difference in the additive force given by equation (20,1), the E never becomes less than COMPE and, therefore, equilibrium configuration is not obtained. To cope with this problem, after x and z coordinates have been obtained within the limits of COMPE, the Precision Focus convergence approach is applied. To demonstrate this method, Figure 17 represents the plot between force FY, which is the end reaction, and the Y coordinate. Pt. H represents a point of intersection, the point which represents the exact y coordinate to which the k end of the cable should strive to reach.

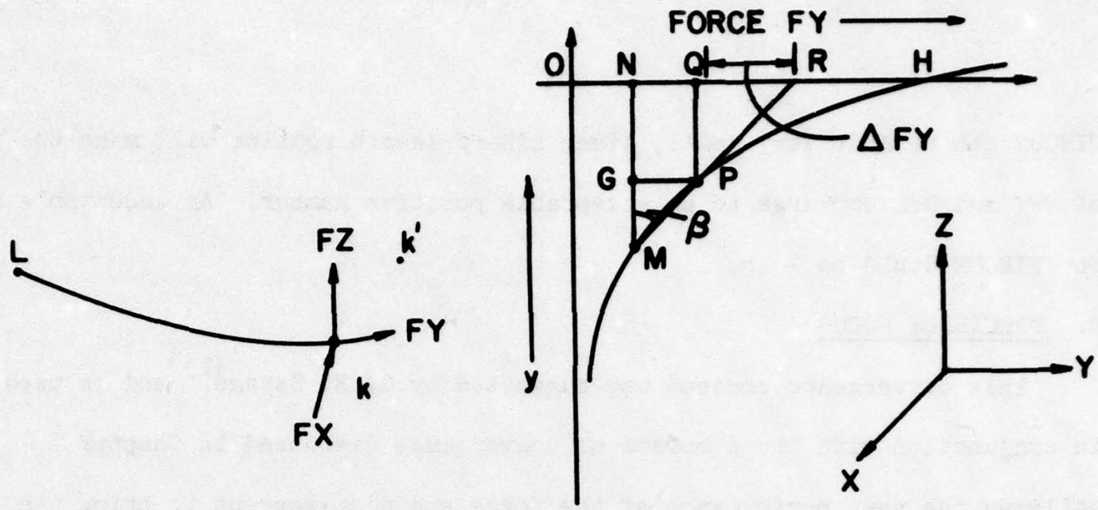

Figure 17: The Precision Focus Concept

If, at the present iteration, the y coordinate (Yp) to which K end of the cable has reached is represented by point P on the curve, then at this point, the force Fy pulling at the end is given by OQ. Also at this point, a record is kept of previous iteration, wherein the y coordinate of the K end of the cable was represented by point M and a force Fy represented by ON was pulling on it.

Then between these two iterations, MP represents the slope of the curve. If β is the angle as shown then

$$\tan \beta = \frac{GP}{MG}$$

where GP = OQ - ON

and MG = MN - PQ

Also at this point, the aim is to increase the y coordinate by $(y_P + PQ)$ and to do this, a force increase represented by HQ will be required to do so. Thus, the new additive force is given by

$$\Delta Fy = \frac{GP}{MG} * PQ$$

This force is added to force (Fy) which coupled with forces FX and FZ would bring the cable to point R and the process is repeated until y coordinate is obtained within the limits of COMPE.

Since the above approach utilizes the past performance and takes into account the slope of the curve, this method seems to avoid the problem posed by the positive number δ getting too small.

Close to point H, the curve gets flat with the result that it is possible to get into a position wherein points P and M are same i.e., PQ - MN = 0. When this happens the control is reverted back to the previous convergence concept. This concept is utilized until x and z coordinates are within the limits of COMPE, at which point control is passed over to Precision Focus again. This provess is then repeated until E $\leq$ COMPE at which point equilibrium configuration is obtained.

E. <u>ASSUMPTIONS USED IN THE COMPUTER MODEL*</u>

In this section a discussion is made of the assumptions made in the computer model. These assumptions are made only for the purpose of convenience and are not necessary from a theoretical point of view.

1. Subroutine VPROFL deals with the current profile. In the program, a profile assuming a series of straight line segments of arbitrary length and scope has been used. However, the analysis developed has been unrestricted. The analysis requires evaluation of the integral as defined by equations (29,3). Thus, any velocity profile could be used as long as the above integral could be evaluated.

   However, if current profile consists of series of straight line segments, as in our case, this integral can be evaluated exactly**. As such, this profile was chosen to write the computer program.

2. On all runs made with the computer program as given in Appendix I, a uniform current profile was used. Current velocity of 0.6739 per sec. was assumed all the way from the bottom (z = o) to the surface. This

*The reader who desires to use the computer program using a different data set than listed in Appendix I is referred to Sub-Sections 6 and 7 of this Sectic

**The evaluation is performed in Appendix II, Skop and Kaplan, "Static Configurat of a Tri-Moored, Subsurface Buoy."

velocity profile, as suggested earlier, was broken up into series of straight line segments. The program is written to take into consideration any velocity profile, but a constant profile was used in this study to provide easy comparison of hydrodynamic forces at all points on the array system.

3. Only one angle of attack of current was used to study the hydrodynamic behavior of the structure. The facility to have a different angle of attack exists in the program.

   It was observed from various computer runs made with the computer program as listed in Reference 9, and modified to suit the facility at the University of New Hampshire, that the worst displacements of the Subsurface Buoy were encountered with the angle of attack of the current as zero degrees ($\beta=0$). As such, for the analysis of the present array system, current with only this angle of attack was used.

4. As described in Chapter IV, a Binary Search Routine was suggested to be used to satisfy the force balance condition in a minimum number of subroutine iterations. Forces in the y - coordinate directions posed the majority of problems. As such, this routine was used only in the y - direction. Should continued use of this program indicate difficulties in the X or Z coordinate directions, then the Binary Search Routine may need to be applied there too.

5. The results that are discussed in Chapter V were obtained by using some of the data listed in a report by R. G. Paquette entitled "Seaspider Hydrodynamics," dated 24 April 1969. This uses a surface buoy along with the subsurface buoy in accordance with the lumped parameter representation. This, however, is not necessary and any other data set can be used.

6. The length of the tie leg array and length of each segment of the tie leg array were determined by the program internally. This also was done only for

simple convenience. If the length of the tie leg is to be given, then a change in the program would have to be made accordingly.

7. The tie leg array is used as a neutrally buoyant array. However, since it is not possible to have this in practice, it was decided to make the array 1% positively buoyant. This was done by using floating objects, with their weights in water as a reference. From this the weight of cable/ft. in water was determined internally by the program. This situation can very easily be reversed. Also, since the length of each segment was determined internally, it was also decided to space the floating objects equally in the segments by the program internally. This is completely for the purpose of convenience.

F. OTHER CONSIDERATIONS

Besides the above cutoff values there are special cases in which the program may never obtain the equilibrium configuration i.e., E may never obtain the value of COMPE. There can be one of the two possible reasons for this to happen.

1. The convergence factor δ, as discussed in Chapter 1, approaches zero as E approaches zero. Consequently, for a very small value of δ no change will occur in the applied imaginary reactions as a result of the significant figure limitations of the computer. When this happens COMPE is too small. This problem can normally be alleviated by either using Precision Focus or increasing the value of COMPE.

2. One of the cable segments has developed zero tension or has gone slack. In this case the array is statically unstable. This condition also results from no change in imaginary reaction. The computer program for the tri-moored array has been equipped to

give out the error printout for the benefit of the user.

In Figure 18, a logical diagram, showing briefly step-by-step description of how the computer program proceeds to determine the equilibrium configuration of the cable system, is presented.

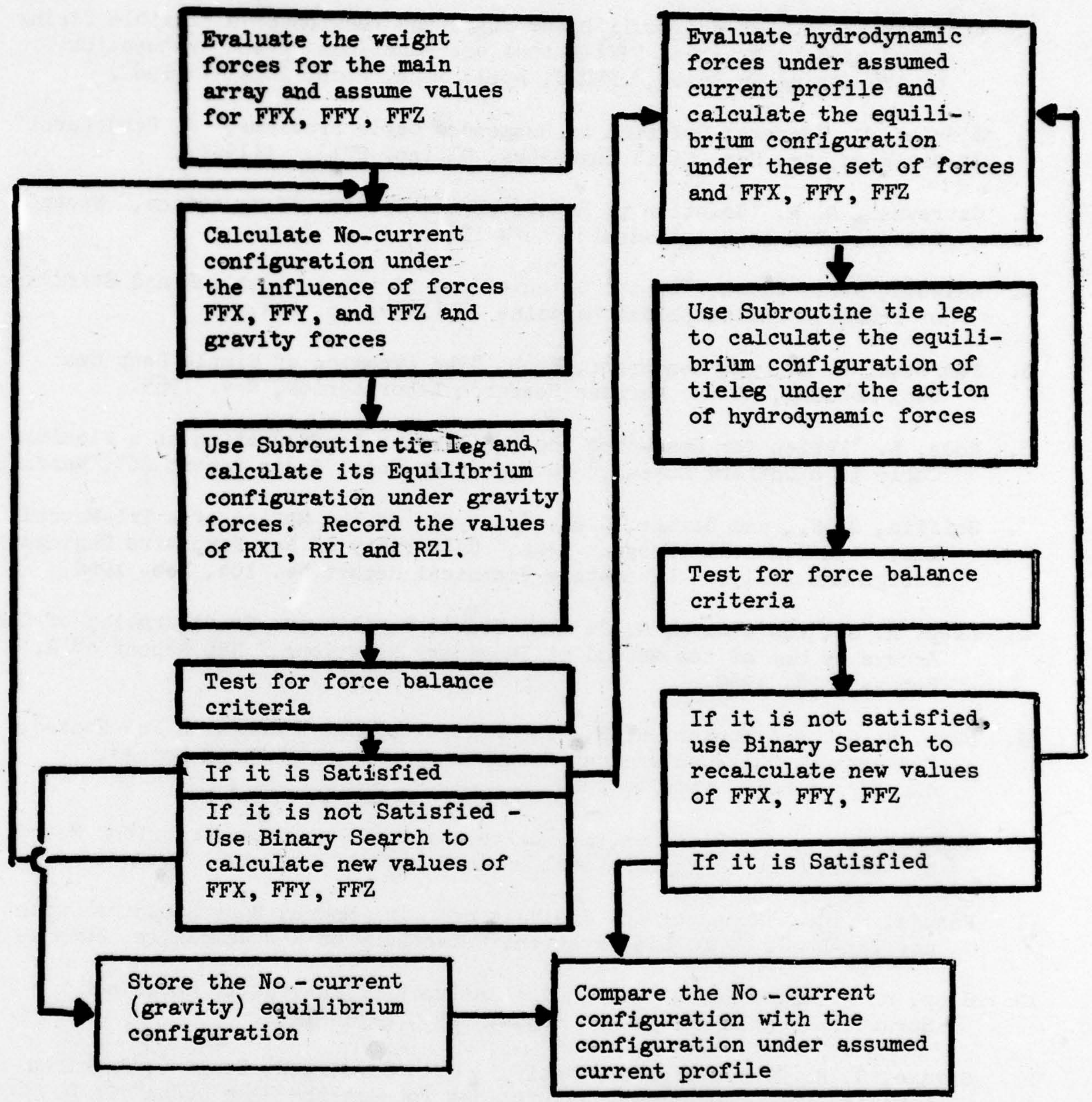

Figure 18: Logic Diagram Showing Step-by-Step Description of Computer Program.

REFERENCES

1. Alekseev, N. I. "On the Equilibrium Shape and Tension of a Flexible String Acted upon by External Forces that are Functions of the Orientation of the String in Space," PMM J. Appl. Math. Mech. 28:1147 (1964).

2. O'Brien, T. "General Solution of Suspended Cable Problems," J. Structural Division, Am. Soc. Civil Engineers, 93 (no. ST1): 1(1967).

3. Ostrowski, A. M. "Solution of Equations and Systems of Equations," Second Edition, New York: Academic Press 1966.

4. Maxwell, James Clark, "On the Calculations of the Equilibrium and Stiffness of Frames," Philosophical Magazine 27 (1864), p. 294.

5. Paquette, R. L., and Henderson, B. E. "The Dynamics of Simple Deep Sea Buoy Mooring," G. M. Defense Research Laboratories, Nov. 1965.

6. Pode, L. "Tables for Computing the Equilibrium Configuration of a Flexible Cable in a Uniform Stream," David Taylor Model Basin Report 687, March 1951.

7. Sniffin, G. N., and Savage, G. H. "Analysis of the Motion of a Tri-Moored Buoy with Neutrally Buoyant Legs," University of New Hampshire Engineering Design and Analysis Laboratory Technical Report No. 104, Feb. 1968.

8. Skop, R. A., and O'Hara, G. J. "The Static Equilibrium Configuration of Cable Arrays by Use of the Method of Imaginary Reactions," NRL Report 6819, February 28, 1969.

9. Skop, R. A., and Kaplan, R. E. "The Static Configuration of a Tri-Moored, Subsurface, Buoy-Cable Array Acted on by Current-Induced Forces," NRL Report 6894, May 14, 1969.

10. Walton, T. S., and Polachek, H. "Calculation of Nonlinear Transient Motion of Cables," David Taylor Model Basin Report 1279, July 1959.

11. Pahuja, S. C., "Modeling and Analysis of a Tri-Moored Buoy Structure with one Tie-Leg", M. S. Dissertation, University of New Hampshire, June 1970.

12. Skop, R. A. and O'Hara, G. J., "The Analysis of Internally Redundant Structural Cable Arrays" NRL Report 7296, Sept. 1971.

13. Savage, G. H. "The Design and Analysis of a Submerged, Buoyant, Anchored Pipeline for Transporting Natural Gas Through the Deep Ocean" Ph.D. Thesis, Stanford University, August, 1970.